The Traces in Use Design Concept

Dissertation

an der Fakultät für Mathematik, Informatik und Statistik
der Ludwig-Maximilians-Universität München

vorgelegt von

Linda Hirsch

MSSc. Human-Computer Interaction

München, den 28. März 2023

Erstgutachter:	Prof. Dr. Andreas Butz
Zweitgutachter:	Prof. Dr. Sheelagh Carpendale
Drittgutachter:	Prof. Dr. Katherine Isbister

Tag der mündlichen Prüfung: 25.5.2023

Abstract

Today's environments increasingly comprise a network of smart and interactive devices that change our perception and relationship with our surroundings. This enables us to access massive information and functionality at our fingertips but may also induce overload and stress and reduce our mental well-being. Additionally, it triggers changes in spatial usage and onsite behaviors, challenging cities to preserve their places' authenticity and social and cultural identity.

These environmental changes push human-computer interaction (HCI) to research the design space of human-environment interaction and develop new design approaches and concepts that support designing for shared multi-user contexts. This also requires designing interactions in relation to the target environment's social, cultural, and spatial conditions to preserve their identity. Experiencing interaction under consideration of these relations fosters sense- and meaning-making, which strengthens users' feelings of belonging, understanding, and social connectedness. However, HCI research lacks design concepts and approaches to contextualizing interfaces so that they can promote this effect.

The thesis approaches the gap with the goal of developing a design concept to contextualize interfaces for meaningful human-environment interaction. For this, I present a three-step process including identifying design approaches and requirements for shared environments, the theoretical development of the design concept *Traces in Use*, and the concept's empirical evaluation in physical, augmented, and virtual reality human-environment interactions.

My work shows that the *Traces in Use* concept can implicitly increase interfaces' social and cultural meaning and, thus, supports their contextualization. The *Traces in Use* concept developed in this thesis is a strong design concept for creating meaningful human-environment interactions, which supports place-making and social connectedness in three different realities. Additionally, the concept responds to the need for preserving places' authenticity and identity by reusing natural and recognizable features of physical reality environments, aka traces, that embody temporal courses and socio-cultural behaviors.

My work also reveals outstanding research questions and opportunities relevant to human-computer and human-environment interactions. This includes evaluating the concept further in different cultural contexts and with user groups or exploring their potential for meaningful mixed-reality contextualization. The thesis approaches a subject of the *HCI Grand Challenges* by providing a concept to create meaningful human-environment interactions and revealing various additional challenges for future research.

Zusammenfassung

Heutige Umgebungen bestehen zunehmend aus einem Netzwerk intelligenter und interaktiver Geräte, die unsere Wahrnehmung und Beziehung zu unserer Umgebung verändern.

Dies ermöglicht uns den Zugriff auf massive Informationen und Funktionen auf Knopfdruck, kann aber auch zu Überlastung und Stress führen und unser geistiges Wohlbefinden beeinträchtigen. Darüber hinaus löst es Veränderungen in der Raumnutzung und im Verhalten vor Ort aus, welches zu Verlusten der authentischen Ortscharaktere und deren soziale und kulturelle Identität führen kann.

Diese Veränderungen führen dazu, dass der Forschungsbereich Mensch-Computer-Interaktion (HCI) den Gestaltungsraum der Mensch-Umwelt-Interaktion erforscht, um neue Designansätze und -konzepte zu entwickeln, die gemeinsame Multi-User-Kontexte unterstützen. Dies erfordert auch die Gestaltung von Interaktionen, die die sozialen, kulturellen und räumlichen Bedingungen der Zielumgebung berücksichtigen, um deren Identität zu bewahren. Interaktionserfahrungen, die diese Beziehungen berücksichtigen, förden die Sinn- und Bedeutungsbildung, womit das Zugehörigkeitsgefühl, das Verständnis und die soziale Verbundenheit der Benutzer:innen gestärkt wird. Der HCI-Forschung fehlen jedoch Designkonzepte und Ansätze zur Kontextualisierung von Interfaces, um diese Wirkung zu fördern.

Die Arbeit zielt darauf ab, ein Designkonzept zu entwickeln, um Interfaces für eine sinn- und bedeutungsvolle Mensch-Umwelt-Interaktion zu kontextualisieren. Dazu stelle ich einen dreistufigen Prozess vor. Dieser umfasst die Identifizierung von Designansätzen und -anforderungen für gemeinsam genutzte Umgebungen, die theoretische Entwicklung des Designkonzepts *Traces in Use* und die empirische Konzeptevaluierung in virtuellen, augmentierten und physischen Mensch-Umwelt-Interaktionen.

Meine Arbeit zeigt, dass das *Traces in Use*-Konzept implizit die soziale und kulturelle Bedeutung von Interfaces erhöhen kann und somit deren Kontextualisierung unterstützt. Das in dieser Arbeit entwickelte *Traces in Use*-Konzept ist ein starkes Designkonzept zur Erstellung sinnvoller Mensch-Umwelt-Interaktionen, welches die Raumverbundenheit und -gestaltung und soziale Verbundenheit in virtueller, augmentierter und physischer Realität unterstützt. Darüber hinaus reagiert das Konzept auf die Notwendigkeit, die Authentizität und Identität von Orten zu bewahren, indem natürliche und erkennbare Merkmale physischer Realitätsumgebungen, wiederverwendet werden, auch bekannt als Spuren, die zeitliche Verläufe und soziokulturelle Verhaltensweisen verkörpern.

Meine Arbeit zeigt zudem weiterführende Forschungsfragen und Möglichkeiten auf, die für Mensch-Computer- und Mensch-Umwelt-Interaktionen relevant sind. Dazu gehört die weitere Evaluierung des Konzepts in verschiedenen kulturellen Kontexten und Benutzergruppen oder die Erkundung ihres Potenzials für eine sinnvolle realitätsübergreifende Kontextualisierung. Die Arbeit nähert sich einem Thema der *HCI Grand Challenges,* indem sie ein Designkonzept zur Erstellung sinn- und bedeutungsvoller Mensch-Umwelt-Interaktionen bereitstellt und verschiedene zusätzliche Herausforderungen für zukünftige Forschung aufzeigt.

Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

Hiermit erkläre ich an Eidesstatt, dass die Dissertation von mir selbstständig und ohne unerlaubte Beihilfe angefertigt wurde.

München, den 28.5.2023

Linda Hirsch

Acknowledgements

There are many people who have supported me throughout the years. First and foremost, I would like to thank my supervisor **Andreas Butz**, for trusting me, letting me explore what I wanted to research, and supporting me in all the different trips and buying (potential) research equipment. I also want to thank my external reviewers **Sheelagh Carpendale** and **Katherine Isbister** for cheering for my work and making me aware of new ideas and directions.

My colleagues were similarly essential to the whole process: **Jingyi Li**, thank you for sharing the roller-coaster ride and the office with me. Thanks to **Christina Schneegass** and **Beat Rossmy** for taking me under your wing when I started. Thank you, **Fiona Draxler**, for your patience and calm. Thank you, **Nađa Terzimehić**, for your positive attitude and encouragement. Thank you, **Sarah Völkl**, for bringing the group together and being the perfect event organizer. Thank you, **Robin Welsch**, for being our statistical expert still supporting us from outside the lab. Thank you, **Sarah Aragon-Hahner**, for your openness and caring heart. Thank you, **Ceenu George**, for your constructive and clear feedback. **Henrike Weingärtner**, thank you for bringing fresh wind into the department and a sane work-life attitude. Thank you, **Yannick Weiss**, for the non-alcoholic drinking times. Thank you, **Florian Müller**, for always seeing the positive and taking the seriousness out of a situation. Thank you, **Jesse Grotjen**, for the coffee times and German-Dutch movie nights. **Steeven Villa**, thank you for meeting me halfway on the veggie ground. **Dennis Dietz** and **Carl Oechsner**, thank you for being so easy to talk to and keeping your door open. **Sophia Sakel** and **Sebastian Feger**, thank you for the fun dancing nights and your great taste in music. Thank you, **Francesco Chiossi**, for introducing me to ECG. Thank you, **Changkun Ou**, for helping make our literature review more transparent. Thank you, **Florian Bemmann** and **Amy Li**, for jumping on the traces train with me. Thank you, **Thomas Weber**, for being such an all-rounder and making such a nice poster with me for the open lab day. Thank you, **Jan Leusmann** and **Luke Haliburton**, for organizing the Christmas party for us. Thank you, **Rifat Amin** and **Svenja Schött**, for being the strong new generation in our lab. There are more amazing colleagues that made my time unforgettable, so I am just gonna say thank you all! The same goes for my students, who were part of many projects and essentially contributed to exploring the design concept.

I also want to thank everyone who keeps or kept the lab running and enables us Ph.D. students to do our job, namely **Franziska Schwamb**, **Christa Feulner**, **Rainer Fink**, **Alexander Wiethoff**, **Albrecht Schmidt**, **Sven Mayer**, **Anja Mebus** and **Heinrich Hußmann**. In association and for their support, I also want to thank **Johanna Pirker**, **Florian Alt**, **Ville Mäkelä**, **Sylvia Rothe**, **Daniel Buschek** and **Thomas Kosch**.

Through the collaborations outside the lab, I also had the honor of meeting many other amazing people that I can't name all. To highlight a few special connections thank you, **Sarah Prange** and **Yasmeen Abdrabou Mahmoud**, for great conference times. Thank you, **Jonna Häkkilä** and **Siiri Paananen** for introducing me to the Sámi culture and inviting me to your lab. Thank you, **Tatiana Losev**, for taking me dancing in Vancouver. Thank you, **Irina Paraschivoiu** and **Eleni Economidou** for being my warm and welcoming Salzburg connections. Thank you, **Tanja Döring**, and the whole team of the Be-greifbare Interaktionsgruppe, **Eva Hornecker**, **Habakuk Israel**, **Raphael Wimmer**, **Jürgen Steimle** and **Dietrich Kammer**.

Last but not least, I want to thank my family and friends outside the research bubble. **Noreen** and **Charly**, thank you for always giving me your honest opinion and emotional support. **Carmen**, thanks for always coming down South whenever something came up. Also, thanks to **Mijke**, **Jerry**, and **Anke**, who explored Bavaria with me on many different adventures. Thanks, **Chrissi** and **Petra**, for bringing home and carnival to Munich. And most importantly, thanks to my parents, **Barbara** and **Dietmar**, and all our four-legged family members, who supported me in finding my own way and always patiently listened to my hard-to-understand research jabbering.

TABLE OF CONTENTS

List of Figures

List of Tables

Abbreviations

Abbreviation	Written Word
AR	Augmented Reality
HCI	Human-Computer Interaction
MR	Mixed Reality
PR	Physical Reality
P	Publication
Q	Guiding Question
RQ	Research Question
VR	Virtual Reality
XR	Extended Reality; here summarizing PR, AR, and VR

Figure 1: Traces of use as manifestations of social and cultural information in the physical reality: a) and c) color traces indicating that something is missing to complete the picture, b) and g) spatial movement traces from a single versus multiple persons, d) and h) rubbed-off surface traces, e) and f) traces indirectly caused by humans through the interaction with another object, and i) a trace of the cultural norm (in Munich, Germany) of rubbing a lion's face for good luck. Picture a) is from an unknown online source. All other pictures are from my collection.

1 INTRODUCTION

The environment also collects data about what is going on and aggregates the data, but provides and communicates the resulting information - hopefully in an intuitive way so that ordinary people can comprehend it easily - for guidance and subsequent actions determined by the people.

– N. Streitz [200]

Figure 1.1: ***Speculative Vision of Smart Cities***. *Media facades stream the latest advertisements in my face from every corner. Autonomous robots rule the street, erasing any traces of the people living there. The city looks like any other place in the world. Only the little glimpses of the architecture and the shiny statues give me an idea of what a culturally rich city it once was. As I walked through the streets, I realized that it wasn't just the physical environment. The people, too, seem to have little connection to their past and each other. Everyone is busy, interacting with their phones with paying little attention to their surroundings. © Seyda Yildiz*

1.1 Motivation and Research Gap

In 2019, Stephanidis et al. [199] presented the *Seven HCI Grand Challenges* that shape the research agenda of human-computer interaction (HCI). These challenges include the shift from human-computer to human-environment interactions [200] deriving from the increasing development of smart, interactive environments that comprise multiple interactive devices in one space shared with multiple users. This requires a shift from single-user to shared and multi-user interaction [217] and concerns physical (PR), augmented (AR), virtual (VR), and mixed reality (MR) environments [199]. With this, human-environment interaction requires designing for varying physical and spatial contexts and mixed cultural and social user groups.

Considering these varying influences in the design process can lead to meaningful interactions by enabling users to understand the experience in connection to their surroundings. This triggers users' sense- and meaning-making beyond the individual and situational experience [94, 148, 171]. Designing for meaningful human-environment interactions contributes to users' well-being by increasing, for example, their social connectedness [175] and awareness [142, 203]. Furthermore, meaningful interaction experiences at and with a place[1] can increase users' feeling of rootedness and belonging [7, 10, 53, 196], two of the most basic human needs [129, 145]. Consequently, aiming for meaningful human-environment interactions can positively contribute to users' well-being in the long-term.

However, human-environment interaction poses two major research challenges: Multiple interactive devices inter-weaved into every aspect of our daily lives [212] can quickly cause, for example, noise or light pollution [59]. With this, they create environmental stressors [40] that can induce information overload and distraction [34, 117, 213] and risk users' mental well-being [59]. The second major challenge derives from redesigning everyday objects and environments into smart, interactive entities that change people's activities, spatial usage, and behavior [56, 73]. These socio-cultural changes stand in contrast to existing norms [138] and bear risks for the authenticity and identity of cities [188]. One example relates to mobile device users. They increasingly detach from their surroundings [127, 165] because instead of freely exploring and engaging, users follow app recommendations on where to go next or are constantly distracted by playing games, listening to music, or chatting with friends on their phones [113]. This moves socio-cultural activities from the physical to the digital space, which increases the social distance between different user groups and impedes identifying with one's surroundings [127].

Alternatively, research suggests to embedded interfaces into the environment and allowing for direct interaction with it [218, 219]. One suggestion is to design for heterogeneous user groups [45] to make interfaces recognizable for some but easy to ignore by others considering the groups' different intentions and interests [124, 190]. Another approach is contextualizing interfaces [38, 119, 205]. Such interfaces are characterized by: i) being embedded into the environment, ii) reflecting the local identity, iii) encouraging individual user engagement, and iv)

[1] A place is here defined according to Dourish [50] as an environment with social and cultural meaning.

inter-personal collaboration and connection [219]. Thus, they support meaningful interaction in shared environments by being socially relevant [219] and personally valuable [166] and enabling direct interaction with the environment [218]. However, both approaches lack design tools and concepts to create such interfaces [10, 34, 117, 186, 195, 213].

Research Gap

There is a lack of design concepts in contextualizing interfaces for meaningful human-environment interactions.

1.1.1 Motivating the Initial Research Context: Historical Sites

Approaching the research gap requires selecting and analyzing the context that should be designed [123] to identify design opportunities for embedding and contextualizing interfaces. In this thesis, historical sites in the physical reality (PR) serve as initial environments. For one, they struggle with losing their significance due to information missing onsite [121], being hard to understand [201] or not being sufficiently engaging [156, 167] or personally relevant [23]. Yet, they are essential for the individual and societal development [107, 108, 189] by, for example, embodying "society's living memory" [14, 123]. Second, due to this challenge, prior HCI research has extensively studied these types of shared environments (c.f., [37, 83, 96, 167]), providing a solid research foundation as a starting point. Third, learning from this prior research identifies historical sites as sensitive design spaces requiring the design of unobtrusive interfaces for onsite interaction [79, 80, 167]. Hence, historical sites could benefit from unobtrusive, recognizable, and meaningful interfaces that foster understanding and connection to the place.

The choice of environment also influences the type of meaningful interaction that is explored in this thesis, considering the need to understand such places' significance and their relevance for contemporary life. This can be approached in multiple ways. Mekler and Hornbæk [148] define the different types from an individual user perspective, which is not sufficient for shared environments as they lack the shared or environmental meanings of places [78]. Consequently, the thesis focuses on meaning triggered by connectedness and coherence [148], and considers the meanings of place framework [78] to reflect the shared meaning-making of multi-user public environments.

1.1.2 Motivating Traces for Contextualizing Interfaces

Based on the historical sites' explorations presented in this thesis and previous work, I explored the design potential of traces of use for contextualizing interfaces. The motivation to research traces originates from the socio-cultural notion of material traces that develop over time and usage [103]. With this, materials and material characteristics of interfaces influence how users understand and make meaning of the interaction experience [69, 110, 179]. Meaning is generated through perceivable material changes, so-called *traces of use* (see Figure 1), regarding how an object was used within a social and cultural construct [43]. This encompasses tangible and intangible values, and the temporal development [103, 179, 215, 216]. For example, when standing in front of a friend's bookshelf, the worn-out book that has been read a thousand times versus others that have barely been touched allows assumptions of its readers' preferences and interests. Thus, this single book trace triggers associations about the reader beyond the individual experience [210]. Traces of use can implicitly elicit sense- and meaning-making about the individual user's behavior and shared social and cultural norms [43, 102, 128], either as a social cue [115, 157], memory cue [98, 150] or, when consistently reoccurring, as behavior pattern [3, 120]. As such, traces incorporate characteristics that help contextualize interfaces and foster meaningful interaction experiences.

Yet, these previous works have not explored the traces' potential to design meaningful interactions in shared environments leading to a lack of empirical knowledge. This further transfers to lacking tools and methods to identify, define, design, and make interactive interfaces and environments with traces (lack of methodology). Traces are also hard to define due to diverging definitions and types and existing similar concepts in the literature (c.f., "breadcrumbs" [137, 155]). These diverging understandings of traces also challenge defining clear design recommendations transferable across application contexts (lack of concept). In this thesis, I narrow these lacks by presenting the development and evaluation of the *Traces in Use* design concept to contextualize interfaces for meaningful interactions in shared environments. This includes a *Traces in Use* framework as a design tool and practical recommendations for the making of *Traces in Use* interfaces.

Research Opportunities

Design Context Historical Sites: Historical sites are sensitive design spaces with high social and cultural value. They are also continuously challenged to preserve and communicate their significance. With these characteristics, they are a suitable research context to start exploring interface contextualization opportunities.

Traces for Meaningful Human-Environment Interaction: Traces of use provide inherent qualities to contextualize interfaces. Yet, their potential has not been explored for designing meaningful human-environment interactions providing research opportunities approached by this thesis.

1.2 Research Structure and Key Findings

This thesis responds to the research gap in a three-step process (STEP I-III). STEP I yields approaches to design for shared PR environments by exploring historical sites. Based on the

results and related work, STEP II explores and conceptualizes traces of use as unobtrusive, recognizable, and meaningful environmental features into a theoretical *Traces in Use* design concept. Lastly, STEP III reports the empirical concept evaluation in physical (PR), virtual (VR), and augmented (AR) reality environments. While excluding the concept evaluation in mixed reality (MR), I will consolidate the empirical evaluations under the umbrella term extended reality (XR) [76] in the further thesis progress.
In this work, I switch from 'I' to 'we' when I refer to papers conducted in collaboration with others. Similarly, I apply the term "environment" to non-specific locations and "place" when discussing a specific place already incorporating social and cultural meaning [50].

1.2.1 STEP I: Analyzing and Designing for Public, Historical Sites in Physical Reality

STEP I presents two design approaches to embed interfaces into shared environments. One focuses on analyzing and reusing contextual conditions for adapting the interface design to the respective context. The other considers the diverging human perception capacities of heterogeneous user groups to design seemingly unobtrusive interfaces for non-users while staying recognizable for interested users. The STEP is guided by the question:

Q1 How can we design embedded interfaces in shared environments that are meaningful and comply with the needs of heterogeneous user groups?

STEP I Key Findings

Physical Design: Exploring historical sites emphasizes that interfaces should support the place's meaning and atmosphere instead of distracting from it [P1, P5, P12]. We identify a natural design approach in a literature survey [P7] that facilitates embedding interfaces seamlessly into different environments while keeping them recognizable to interested user groups. The approach uses materials, their characteristics, and objects in the environment [P2] for the interface design so that users can focus on the place's social and cultural identity [P1, P5].

Perceptual Perspective: Considering heterogeneous user group needs, we further explore the inattentional blindness [P12], a phenomenon from perceptual psychology that describes failing to notice something due to a lack of attention [192] and its effect at a public, historical square. Our results show that designers can account for the inattentional blindness of non-users when contextualizing interfaces in public places while keeping them recognizable by users by adapting the interface' seeming task-relevance [P12]. For this, the carrier[a] shape and appearance should reflect task relevancy [P12].

Foundation Design Concept: Both design approaches [P7, P12] respond to Q1 regarding the embedding of interfaces or complying with heterogeneous user group needs.

However, neither approach tackles inter-personal connections, which limits the interfaces' contextualization. These findings constitute exploring alternatives to increase meaningfulness in the form of traces in the next step.

Core publications: [P1], [P2], [P5], [P7], [P12]

[a] The term 'carrier' refers to the object containing all technology for the interaction [219]. The carrier extended through technology results in an interface.

1.2.2 STEP II: Concept Development - Exploring and Conceptualizing Traces of Use As Design Features to Contextualize Interfaces

STEP II reports the process of identifying traces of use that are natural for urban environments as potential design features to create contextualized interfaces. By this, STEP II considers STEP I findings but additionally explores interface contextualization concerning social connectedness and local identity. STEP II informs about i) recognizable characteristics and types of context-specific natural traces for urban environments and their interpretation, ii) design-relevant trace characteristics and dimensions for conceptualizing traces into the *Traces in Use* design concept. The guiding question in STEP II is:

Q2 How can we conceptualize natural traces of use for designing meaningful human-environment interaction?

STEP II Key Findings

Natural Traces of Use Characteristics for Interface Contextualization: The paper [P10] finds that traces of use are recognizable and natural features of urban environments. The meaning-making of traces is highly influenced by the context and the trace characteristics [P10, P11]. Furthermore, [P11] identifies approaches to create *Traces in Use* designs. Both publications highlight design dimensions for creating *Traces in Use* interfaces, which we set into relation in the *Traces in Use* framework [P3, P6] (see Figure 3.1).

Theoretically Evaluated *Traces in Use* Concept: We present the idea of traces as a design concept along urban interaction design challenges [P13] and evaluate the concept theoretically in expert interviews for PR [P6] and VR contexts [P3]. Findings confirm the successful theoretical conceptualization of traces into the *Traces in Use* concept for contextualizing interfaces and environments implicitly (Q2). Furthermore, interview results emphasize the vast *Traces in Use* design space when extending the physical traces to XR traces. In this context, the *Traces in Use* concept also enables manifesting and sharing temporal courses and other, so far intangible information such as heartbeat or socio-cultural behaviors [P3, P6].

Core publications: [P3], [P6], [P10], [P11], [P13]

1.2.3 STEP III: Evaluating The Traces in Use Design Concept in XR Environments

Step III evaluates and refines the *Traces in Use* concept through empirical studies in PR, AR, and VR and, thus, explores the concept beyond PR and historical sites for other meaningful human-environment interaction contexts. The types of traces, their integration, and their design were adapted to the respective technology and context. The guiding question is:

Q3 What (varying) effect does the *Traces in Use* concept have when applied to contextualize interfaces in shared environments in different realities?

STEP III Key Findings

***Traces in Use* for XR**: The concept *Traces in Use* can be confirmed for contextualizing XR interfaces and providing meaningful experiences in shared PR, AR and VR environments [P3, P4, P6, P8]. However, the empirical results also show current challenges regarding the traces' aesthetics and scalability [P6, P9]. The concept classifies it as a strong design concept for contextualizing interfaces and designing meaningful human-environment interactions [P6]. Responding to Q3, STEP III further highlights diverging and common design considerations when applying the concept in different realities.

Core publications: [P3], [P4], [P6], [P8], [P9]

1.3 Contribution

The increasing development of ubiquitous, smart environments [199, 212] requires considering interactions and their impact on contextual influences and dependencies beyond the individual. Consequently, the shift toward human-environment interaction is already happening while HCI research is behind in developing approaches, concepts, and tools to design for this change of perspective. The thesis contributes with two design approaches and a concept for human-environment interaction by exploring context-specific natural features [P1, P2, P7] that can be recognized by interested users but easily ignored by others [P12]. By this, the approaches support physically embedding interfaces that counteract environmental stressors [40, 59, P13] and comply with heterogeneous user group needs [P6, P12]. For increasing the interfaces social and cultural meaningfulness, I developed the *Traces in Use* design concept [P3, P6, P10, P11, P13]. The concept is based on the two design approach [P7, P12] by conceptualizing context-specific natural and recognizable features, namely traces of use. By focusing on designing for meaningful human-environment interactions, the thesis aligns with Frauenberger's [61] reflection on the next (fourth) wave of HCI and the need to design meaningful relations instead of user experiences. Physical material traces have been used to analyze and reflect meaningful relationships for a long time [103, 110, 128] because they embody memories [98, 150] and behaviors [3, 115, 120, 157]. This thesis extends prior work with a deeper understanding of traces in HCI design and their potential to reflect the socio-cultural, temporal, physical, and spatial relationships in an interface [P4, P6, P8, P9]. By this, the thesis narrows the lack of knowledge in HCI research. The insights further provide hands-on recommendations for making contextualized *Traces in Use* interfaces, narrowing the lack of methodology. Lastly, the thesis demonstrates application scenarios of the *Traces in Use* design concept for varying contexts and realities, and structures and defines traces in HCI compared to other related concepts. Consequently, the thesis contributes to narrowing the lack of concept regarding traces within HCI. To this end, the thesis further highlights research questions for future work about *Traces in Use* interfaces in other socio-cultural contexts, the scalability of *Traces in Use* for "more-than-human" designs when used over a longer time, and ethical considerations and ownership when tracking and reusing traces for designing XR.

Research Contribution

The thesis contributes two design approaches and a concept for designing meaningful human-environment interactions. By this, the thesis narrows the research gap and opens the design space of XR traces for implicitly increasing socio-cultural understanding and connectedness. Further, the work provides practical insights considering tools and classifications supporting future design processes.

2
BACKGROUND AND DEFINITIONS

This chapter embeds the thesis into current research and defines terms relevant for further reading. Driving topics are human-environment interaction, sense- and meaning-making, and the knowledge and usage of traces in research.

2.1 Human-Environment Interaction

Human-environment interaction is a research direction focusing on the interactions in shared and smart environments [199, 200] that are enhanced with embedded sensors and actuators [75, 111]. In the movement toward human-environment interaction, designers and researchers alike are challenged by turning everyday objects and architecture into interactive entities [200, 217]. This includes the research challenges of enhancing physical materials and environments with technology [P2, 91, 217], finding strategies and approaches to embed technology into the environment to be unobtrusive and recognizable [117, 208, 213], and providing interactive experiences that foster well-being, and social and cultural engagement [5, 18, 32, 59, 99].

2.1.1 Contextualizing Interfaces and Environments

By contextualizing interfaces, previous work has explored interfaces that relate users to their surroundings and other places users [38, 46, 90, 119]. One of the main purposes of contextualizing interfaces is to provide meaningful experiences to users by being socially relevant [219] and valuable for the individual [166]. The making of such interfaces is a continuous research challenge also due to the lack of design tools and methods. Additional to Wouters [219] four design aspects to contextualize media facades, there are only the three contextualization perspectives, namely the content, carrier, and environment perspective, introduced by Vande Moere and Wouters [205] so far. These three perspectives provide a guideline as to which perspectives must be analyzed and considered in the design process to contextualize interfaces [205]. They define content as the displayed information to the users, environment as the surrounding physical conditions, spatial affordance, and onsite activities, and the carrier as the "broadcasting medium" [205]. Both works [205, 219] provide the basis for designing the contextualized prototypes presented in this thesis.

2.1.2 Unobtrusive Interfaces and Inattentional Blindness

In shared environments, interfaces must be non-disruptive to comply with the heterogeneous user group needs of interested and non-interested users [45]. Thus, previous research has, for example, explored designing unobtrusive interface [122, 177]. The unobtrusive design has various definitions [126] and is determined by adapting the interface design to the context [185] and the attention and workload it requires from the user [72]. As part of the latter, inattentional blindness occurs when the user's attention is focused on a primary task so that the other visual input presented in the center of our visual perception is missed [140, 192]. This means that users concentrated on a specific task can easily overlook interfaces right in front of them. Inattentional blindness has been exploited to, for example, decrease rendering times without users noticing it, i.e., [36, 172], or for hiding task-irrelevant information [164]. Consequently, the interface is unobtrusive for some, while visible to others due to its role and meaning for the users' task at hand. In one of the projects [P12], I show that inattentional blindeness can be exploited to design for heterogeneous user groups in shared environments.

2.2 Sense and Meaning

Meaningful interactions [154, 199] improve the quality of an interaction [148] by responding to users' needs and values [84]. According to Mekler and Hornbæk [148], such designs can trigger the feeling of connectedness, give purpose, and provide coherence, resonance, and significance. They allow users to make sense of the experienced [171], which is the process of reflecting on and relating to the experience beyond the situational interaction [17, 94]. Additionally, sense-making enables building meaningful relationships [24, 94]. In comparison to sense-making, meaning-making is the process of reflecting upon and understanding the meaning of an experience on an individual, personal level [146, 222]. Designing meaningful interactions is, however, complex [133] and challenging [11] because a *"meaning"* is volatile and continuously changes depending on the contextual influences and social dynamics [11, 116]. Altogether, sense-making is a component to create meaningful interactions [148] but the processes of sense- and meaning-making differ. In this thesis, I present different measurements and approaches to create meaningful interaction with a focus on sense-making.

2.2.1 Meaningful User-Place Relationship

In shared environments, meanings are defined from multiple perspectives, the individual (*"self"*), the conditions onsite, including the spatial affordance and place usage (*"environment"*), and through a local community's cultural and social conditions, called *"others"* [78]. These perspectives emphasize the role of the environment's architectural and spatial features [6, 97] and socio-cultural context [82, 133, 143]. The multi-dimensional influences require distinguishing between aspects and identifying relevant information that should be transferred into the interface design to foster users' sense- and meaning-making [186, 204]. Schoffelen et al. [186] call this process the visualization of background stories to foster user engagement, sense-making, and reflection.

From an individual user perspective, meaningful onsite interactions can result in place attachment [74, 119, 160, 173], which indicates how much a user identifies with a place (*place identity*) and depends on it (*place dependency*) [23]. Users' well-being, the feeling of ownership, and responsibility toward a place increase through such attachment [7, 29, 181]. Consequently, the attachment triggers users' needs to protect and preserve the place [191]. This further makes it an exciting topic for HCI and cultural heritage research [1, 184]. Place attachment is also an established indicator in HCI to evaluate the user-place relationship [10, 53, 90, 196].

2.2.2 Meaningful Interaction through Social and Local Connectedness

Meaningful interactions can be designed by enabling users to connect with others and their surroundings [148] socially. This includes triggering the feeling of cultural belonging and building a local identity [8, 15] or designing for social connectedness and awareness [9, 22, 198]. Each of these design goals can contribute to users' well-being because humans are social beings by nature with an inherent urge to belong [31, 198]. Designing meaningful interactions by fostering social connectedness or engaging with the local environment are concepts universally applied in PR [161], AR [90, 119] and VR [187]. Similarly, they are core concepts considered in this thesis.

2.3 Traces in Research

Lastly, I provide a derivation of traces by relating it to research fields outside HCI, HCI research examples, and other, similar concepts such as nudging or social cues.

2.3.1 Traces Outside HCI

The qualities of traces have been exploited or taken as complementary measurements in multiple research fields other than HCI, such as social science (e.g., [128, 210]), anthropology (e.g., [63]), architecture (e.g., [27, 123]), and archaeology (e.g., [19, 20]). Archaeologists look into the material culture to deduct habits, social norms, and spatial conditions of former periods [19, 20]. Their definition and application of traces overlap closely with the ones from materials experience design [109, 178, 179]. Further, anthropologists and social science derive assumptions from traces about culture, techniques, contemporary society [63] and behavior [128, 210]. In architecture, traces reveal how humans use space; much like the desire path[1] paving a path through the grass. Additionally, they contribute to the "visible age" [123], and, thus, to a building's authenticity and atmosphere. Without going into more detail, this little excursion outside the field of HCI shows that traces, and particularly material traces, have already been used for analysis purposes of human behavior and activities for a long time. They confirm traces as evidence of human interactions that reveal meaningful relations.

[1] `https://en.wikipedia.org/wiki/Desire_path`, last accessed July 31, 2023.

2.3.2 Designing with XR Traces

Returning to the HCI perspective of traces, previous research has tracked and applied traces of use for analysis and interaction purposes. Digital traces, for example, have been analyzed for adapting system designs [12, 134] or feeding recommender systems [100, 211]. In comparison, others have explored the physical manifestation of time that material traces can represent; e.g., in the form of ephemeral sand traces [51] or those that develop over long-term use [49, 67, 130]. Augmenting a museum exhibition, traces of use have been displayed on artifacts to emphasize how those had been used in former times [180]. Applying AR traces communicated the artifacts' tangible affordance that museum visitors could not experience [180]. Other work has augmented environments through projections to display movement traces to increase social and spatial awareness [88, 151]. Video games [104, 118, 168] such as *Horizon Zero Dawn* [64] or *No Man's Sky* [85] integrate similar notions to traces into their game environments to help players navigate or provide indications about other players' gaming experiences. All these examples show that the idea of "traces" in HCI is not new. However, it is also a fuzzy concept that lacks approaches to design and apply it systematically.

2.3.3 Distinguishing Traces from Nudges, Affordance, and Social Signifier

Traces are similar to and partly overlap with other concepts considering nudges [33], affordance [158], and social signifiers [115, 157]. Nudges trigger users to reflect on or manipulate behavior changes [81]. Traces can be used as nudges by, for example, highlighting touched surfaces in a public elevator – users could replicate the same touch or try to avoid it (thus, change their behavior). However, traces are not designed to manipulate users or trigger a behavior change. Instead, they are supposed to increase awareness and contextualize. Furthermore, affordance describes an object's quality to infer through its shape and design how users can interact with it [158]. Traces can accumulate and represent behavior and interaction patterns [3, 120] but also resemble highly personal experiences without a clear pattern [150, 202]. Additionally, in contrast, traces can incorporate high social and cultural meaning. Lastly, social signifiers include environmental changes, e.g., a freshly brewed cup of coffee on the table, that incorporate social meaning and enable users to make assumptions about others' behavior, character, and activities [157]. As such, I define traces as a specific type of social signifier as also discussed more in-depth in [P6]. This paragraph shows the touch points of the different concepts and clarifies how traces differentiate for interaction design.

3
THE TRACES IN USE DESIGN CONCEPT FOR EXTENDED REALITY

Placeness is created and sustained by patterns of use; it's not something we can design in. On the other hand, placeness is what we want to support; we can design for it.

– S. Harrison and P. Dourish [82]

This chapter presents 13 research papers and their contributions to developing a design concept to create meaningful human-environment interactions. In STEP I, this includes the publications [P1, P2, P5, P7, P12] that explored and defined design approaches to support an unobtrusive, yet recognizable interface embedding into the environment. STEP II presents the publications about the *Traces in Use* concept development, from identifying traces of use as design features for the urban realm [P10, P11, P13] to the theoretical concept and framework development [P3, P6]. The papers [P6][1] and [P3] occur in STEP II and STEP III because I separated the theoretical concept development (STEP II) from its empirical exploration and evaluation in PR [P6, P8], and VR [P3] (STEP III). The last STEP is enriched by exploring AR- [P4] and VR-specific traces [P9]. Each STEP contains its own research questions, a short introduction, and details of each publication.

3.1 Step I: Designing for Public, Historical Sites in PR

STEP I focuses on researching design approaches and concepts to embed interfaces unobtrusively and recognizably into shared environments along the example of historical sites, namely, a historical cemetery and a square in the city center of Munich. These sensitive design spaces [95, 167] in combination with the challenge of designing for heterogeneous user groups leads to the following research question (RQ1):

RQ1 How can we design physically embedded interfaces that comply with the contextual requirements of historical sites as shared environments of heterogeneous user groups?

I approached RQ1 from two perspectives: i) adapting the physical interface design to the environment [P1, P5] by applying a natural design approach [P2, P7], and ii) exploiting users' limited perception capacities [P12] to make interfaces disappear through inattentional blindness. Both perspectives influence an interface's perceptibility and, thus, contribute to embedding interfaces unobtrusively and recognizably [35, 68, 114]. In total, this STEP comprises five publications that include qualitative and quantitative analysis methods, two field studies, two literature surveys, and speculative design to respond to RQ1.

[1]The papers [P6] and [P9] are currently under revision.

3.1.1 Physical Interface Design

Aiming to adapt the interface to the surroundings of a historical cemetery, we followed Weiser's notion of calm technology [212, 213]. His vision to create unobtrusive interfaces by seamlessly embedding technology into everyday materials and objects has been explored in various work or home contexts [114, 163]. In comparison, public contexts have found little consideration and are mostly related to screen-based display design [2, 30, 41, 162].

Two publications are based on studies conducted at the historical cemetery. By applying speculative design methods, diegetic artifacts [25], in [P5], we found that users value the place as-is and would want to preserve its meaning and architecture for today and the future. The finding aligns with prior work's discussion about the diverging built environment qualities from interactive technology. The built environment is built for long-term use, durable, and persistent, whereas interactive technology and devices are fast-developing and have short lifetimes [139]. Study participants [P5] suggested embedding interfaces only short term while supporting the place's timelessness. By this, embedded interfaces can and should be regularly adapted to spatial conditions and continuously evolving societal norms. For example, phone usage can be perceived as disrespectful [80] but could become entirely normal and accepted in the future [P5]. Both of the cemetery-related publications [P1, P5] identified the need to emphasize the cemetery's natural atmosphere and meaning. Interfaces should support preserving the place's character, including monitoring users' behavior onsite to assure a respectful interaction with the place and others [P5].

The second cemetery design space publication [P1] additionally explored a natural design approach by prototyping and evaluating a birdhouse-inspired interface onsite. This natural design approach is similar to "hiding" technology in everyday objects [114] by identifying and redesigning materials and objects that are natural for the target environment. We derived the approach through a literature survey following the PRISMA [136] in the ACM Digital Library [P7]. Our survey findings emphasized that natural design is context-specific, which is determined by users' social and cultural backgrounds, and the spatial and physical conditions onsite. For the particular cemetery context, birdhouses are reoccurring objects and part of the natural environment. Additionally, we chose wood to make the birdhouse interface because it is a natural material for the cemetery and conveys a certain warmth [176]. Such material characteristics are essential to consider in the design process because they influence the material-place relationship and, consequently, how users perceive and make meaning of a place [P2]. Testing our interface onsite confirmed the natural design to support seemingly embedding interfaces into the environment and keeping the place's atmosphere. Yet, participants also perceived it as too unobtrusive and suggested improving its affordance [P1].

3.1.2 Perceptual Perspective

Alternatively, we showed that we could exploit humans' limited visual perception capacities [153, 206] to embed interfaces to be obvious and recognizable for interested users but stay unobtrusive and non-disruptive for non-users [P12]. This approach is linked to the challenge of accommodating multiple (non-)user groups in shared environments [45] and providing information "ready to use" [34] if needed [212]. In this process, the information is made available in the periphery of attention [13]. It also means that interfaces are seamlessly embedded into the shared environment, which relates to the natural design approach [P7] from above.

In our work, we tested the inattentional blindness effect [192] with five embedded interfaces and two user groups (N=40) at a public, historical square in the city center of Munich. Three interfaces were permanently installed. We added two interfaces by considering the natural design approach and identifying context-specific natural materials and spatial conditions. This resulted in a translucent concrete information box positioned in a passage with darker light conditions and a QR code made of concrete placed at an entrance. Based on Leifer's scale for implicit interaction [132][2], we had classified both self-developed interfaces as relatively unobtrusive designs. With these interfaces, we conducted a mixed-method field study in which participants were split into interested and non-interested user groups. Participants then self-reported artifacts or scenes relevant to their task using picture-taking [152] and rated the interfaces' unobtrusiveness. Our results confirmed that human's limited perception capacities could be exploited by design for heterogeneous user groups in shared environments.

In this paragraph, I reflect on this paper's relevant findings that supported my decision to look into traces next. Please refer to the original publication [P12] for more details about other findings. We found that the recognizability of our embedded interface was stronger influenced by top-down processing than bottom-up[3] and the perceived affordance. This confirmed the interfaces' unobtrusiveness. At the same time, it shows that an interface's recognizability in shared environments can be achieved by triggering users' semantic interest [87, 174] and explicitly designing for task relevance [86]. For example, the QR code was classified by us as the most unobtrusive interface of all five. Yet, it is also a familiar, known interface that enables access to further information. Hence, it was considered task-relevant by most of the participants that were supposed to perceive it but almost entirely missed by the other group (except 3 of 20 participants). Accordingly, users' prior knowledge and experiences impact an interface's recognizability through previous meaningful interactions [52, 86].

3.1.3 Summary & Next Steps

STEP I presents two approaches to embedding interfaces while complying with the requirements of historical sites as shared environments and heterogeneous user groups

[2]Leifer [132] introduced a two-axis scale (from foreground to background and from reactive to proactive) to classify interfaces and the interaction with them according to their prominence in an environment.

[3]Top-down processing is the process of making sense of the perceived visual input through previous experiences and prior knowledge [52, 86]. In contrast, bottom-up processing is mainly a reaction to salient stimuli [60, 131] such as strong color contrasts or flickering lights [170, 209].

(**RQ1**). The natural design approach shows that interfaces developed with the context-specific natural design features can be seamlessly embedded into a public, shared environment but might be hard to recognize [P1, P5, P7]. Nonetheless, the approach contributs to the place's atmosphere [P2]. The second approach considers a user-centered perspective. It shows that interfaces are easier recognizable when the carrier reflects a familiar and task-relevant shape and design as it becomes meaningful for the task at hand [P12]. Additionally, by aiming for top-down processing, the interfaces' shape and appearance already represent meaning to users due to the connection to users' prior knowledge and experiences. The second approach considers the natural design approach by prototyping with context-specific natural materials. As such, it builds upon previous learnings and approaches the interface design from another perspective. To this end, STEP I contributes to contextualizing [219] interfaces by providing two approaches for embedding physical interfaces, encouraging individual engagement and reflecting the local identity through the material and carrier choices. However, the combination of these approaches was still limited in reflecting the historical value of the places and did not trigger any social or cultural connectedness. Based on this, I looked into traces of use and their potential to contextualize interfaces for interactions with incorporated socio-cultural meaning in shared urban environments and could strengthen the local identity next.

3.2 Step II: Concept Development - Identifying and Exploring Traces of Use For Contextualizing Interfaces

Traces incorporate meaning as the embodied evidence of previous interactions, behaviors, and experiences [103, 178, 182]. They have been researched in various forms by multiple research fields outside HCI, e.g. [63, 103, 128, 210]. As such, the idea is not new to use traces to gather insights about a situation [120, 210], and to trigger social and cultural awareness and understanding [48, 102, 151]. However, there is currently neither a clear design concept nor a common understanding of traces in interaction design nor knowledge about their potential for designing meaningful human-environment interactions.

In this STEP II, I conceptualize natural traces of use guided by the findings of STEP I and the following research questions:

RQ2.1 What are natural traces of use characteristics relevant for designing meaningful human-environment interactions?

RQ2.2 What influences the meaning-making and understanding of *Traces in Use* interfaces?

At first, I present the collection, analysis, and selection of context-specific natural and recognizable traces of use characteristics for design [P10]. This follows an exploration of the making and understanding of interfaces with traces through physical prototyping, an elicitation study, and outdoor bodystorming [P11]. Both publications contribute to the *Traces in Use* concept development by following structure-mapping. Structure-mapping is relating and cognitively transferring natural features into a design feature [54, 144, 183]. The concept is first discussed along human-environment interaction challenges [P13] before being refined and theoretically evaluated in expert interviews [P3, P6]. Five publications [P3, P6, P10, P11, P13] contribute to the *Traces in Use* concept development and theoretical evaluation.

3.2.1 Traces of Use for Designing Shared, Urban Environments

In [P10], we first assessed whether users perceive traces of use as recognizable and meaningful in shared contexts. We photographed traces of use examples collected in urban environments, such as rubbed-off statue parts or scratches along walls. The photographs were clustered and evaluated in an expert focus group (N=4), followed by an online survey to test the traces' recognizability across a broader audience (N=52). We chose digital photographs because such visual representations can convey tangible and material characteristics [57, 70, 71] and enabled us to analyze overlapping recognizable features with a processing script. With this mixed-method approach, our findings included an overview of trace types and characteristics recommended for the design of meaningful interfaces and for ignoring in the further process [P10]. For example, participants appreciated the patina effect – which is "any fading, darkening, or other sign of age on an object that occurs through a natural or artificial aging process" [89, 130] – because they associated it with strong social bonds and cultural traditions. Furthermore, we identified seven material design dimensions that support the making of trace design and influence their meaning-making [P10]. Based on the identified trace characteristics, we explored four making strategies of trace interface designs and tested a sample set of interfaces in an elicitation lab study [P11]. We compared natural traces of use designs with clean and abstract designs without being embedded into context to explore the traces' effect, excluding external influences. The results confirmed the natural trace design as the design choice for outdoor environments and the abstract design for indoor environments. Furthermore, the abstract designs were perceived as easier to understand and control. Yet, the natural trace designs invited more to explore. They also triggered a sense of social connection and increased the affordance *"simply because others have already used it."*. Both publications [P10, P11] provide trace types and characteristics relevant to create natural, recognizable, and meaningful interfaces for urban environments.

Responding to **RQ2.1**, the two presented publications serve as the basis to conceptualize traces of use by using them as interaction metaphors while ignoring disturbing trace characteristics. Further, they confirm the traces as context-specific, natural, recognizable features of urban environments that can convey social and cultural meaning even without being embedded into context. They comply with STEP I design approaches and respond to other contextualization characteristics by adding socio-cultural meaning to interfaces.

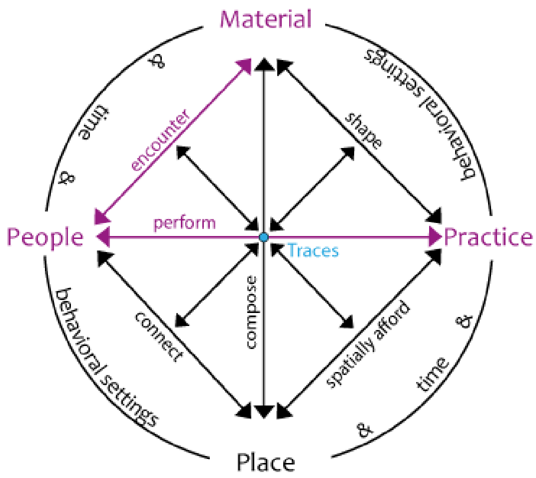


Figure 3.1: The *Traces in Use* framework as presented in [P3, P6]. The purple color reflects the materials experience design framework [69, 178] that this framework is based on.

3.2.2 From Traces of Use to *Traces in Use*

We developed the concept *Traces in Use* iteratively. In [P13], we first presented and discussed the concept as a sustainable approach to creating unobtrusive, recognizable, and meaningful urban interfaces by reusing and recycling existing materials and their characteristics[4]. Additionally, part of the concept is reusing familiar, natural features [54, 144, 183] that are either created by or trigger the impression of having been created by humans. The *Traces in Use* are clearly shaped, always purposefully designed, and relate to a specific interaction and usage intention. In contrast, they must not be generated by actual user interaction.

We also developed a framework (see Figure 3.1) as a design tool for contextualizing interfaces with the *Traces in Use* concept. It is based on the materials experience design framework [69, 178] and considers all design dimensions that influence the traces' design and meaning-making (**RQ2.2**). In return, the traces influence the meaning-making of each dimension and reveal entanglements[5] between them. We evaluated the framework theoretically in interviews with experts in urban interaction- (n=4), traces- (n=4), and virtual reality design (n=4), conducting an inductive thematic analysis [28]. All experts concurred with the framework's relevance as a design tool to design *Traces in Use* interface. The results are presented for the urban interaction- and traces design expert in [P6] and in [P3] for the VR designers.

Regarding the concept, the results emphasized the opportunity for non-physical material

[4]The 17 United Nation Sustainability Goals (`https://sdgs.un.org/goals`) includes, among other goals, number *3: Good Health and Well-being* and *11: Sustainable Cities and Communities*. By reducing environmental stressors while making shared environments engaging, we see the *Traces in Use* concept contributing to both goals.

[5]Entanglements are the sum of interrelations and correlations between people, places, and objects [178, 182].

traces and the challenge deriving from the traces' ambiguity. Their meaning and ownership change depending on the reality and type of traces. For example, virtual traces need to be enabled by design. Accordingly, the system designer decides what traces to track and display to what users. In contrast, the traces provide the opportunity to reflect the temporal course and long-term relationships, e.g., one of our experts stated: *"I can see there's a memory, [...] stored in the traces"*. To this end, applying the *Traces in Use* design concept can extend the type and amount of information communicated through an interface.

3.2.3 Summary & Next Steps

STEP II presents the *Traces in Use* concept development. This includes identifying traces' types and characteristics that are natural, meaningful, recognizable [P10, P11] and can be exploited for contextualizing interfaces. The STEP further provides the concept definition [P13] and the development and theoretical evaluation of the *Traces in Use* framework [P3, P6]. The results also emphasize the concept's potential for realities other than PR and indicate the need for further empirical evaluations, which I present in STEP III.

3.3 STEP III: Evaluating The *Traces in Use* Concept for XR

The last STEP in this thesis comprises the empirical concept evaluation and the methodological approaches of creating *Traces in Use* interfaces and environments. Five papers contribute to exploring and evaluating the concept and its practical application within design processes applying mixed-methods. Two focus on PR traces evaluated in two field studies and an online survey [P6, P8], one presents AR traces [P4], and another two explore the concept in VR lab studies [P3, P9]. By exploring the concept for different XR contexts, this STEP follows the research questions:

RQ3 How does the *Traces in Use* concept support contextualizing interfaces for meaningful interactions when applied in different XR environments and application contexts?

In contrast to STEP I and II, **RQ3** can only be answered by comparing the findings of all publications, which is presented in the summary of this STEP. Designing traces for different realities also requires identifying what context-specific natural [P7] means for each environment and technology. However, the question of what is "natural" for VR and AR is deeply philosophical and has already engaged many researchers (e.g., [21, 26, 159]). It is out of the scope of this thesis and will only be discussed regarding the trace design and its implementation. Additionally, AR traces were explored in a small scope compared to PR and VR traces and are, thus, presented at the end of this section.

3.3.1 Empirical Evaluation and Design of PR Traces

I build on the work presented in STEP I and II by applying the *Traces in Use* concept to contextualize interfaces for two urban environments [P6] and one public transport situation [P8]. In each project, we used the *Traces in Use* framework as a tool to analyze the context and transfer the learnings into the interface design. In [P6], we followed a *research in and through design* approach [44] by evaluating how current design processes can be extended through our *Traces in Use* framework and with what methods we can complement the design of *Traces in Use* interfaces (research *in* design). Additionally, we gained insights into contextualizing urban interfaces by employing different design methods and practices such as prototyping or concept development (research *through* design).

We analyzed two urban places, the historical square used in [P12] and a community area. We developed and tested three interactive, tangible interfaces (see Figure 3.2), the Storyteller as more contextually-neutral interfaces tested in both places and two stronger contextualized interfaces for one place each, an interactive lion statue and drum. The making process is summarized in an annotated portfolio style [66] for each interface as presented in [P6]. The purpose of contextualizing interfaces for these two places is to provide meaningful interactions by engaging and connecting users with their surroundings and other place users. As both places are frequently visited places, the interfaces needed to be unobtrusive and recognizable in the environment. Thus, we designed carriers, materials, and traces to complement the respective place. Testing the interfaces with 20 participants at each location confirmed their suitability and well-embeddedness at each place. We conducted the study as applied in [P12] followed by user testing the interfaces. Working with material traces in this project, we found that participants liked the experience and related the traces to other users' previous interactions and happenings at the places. The trace designs conveyed an authentic aged appearance, which supported users' connection-making and understanding of the places' history in both cases. Three of the participants raised hygiene concerns. Another finding related to the carrier shape and positioning in place. Both essentially influenced the interfaces' recognizability and understanding in addition and relation to the trace design. Based on that, we extended Wouter's [219] contextualization perspectives about the material perspective. It states that material choices and their characteristics influence users' meaning-making in addition to the content, carrier, and environment. This also confirms the *Traces in Use* designs to foster meaningful user interactions in shared PR environments.

In the other publication [P8], we applied the *Traces in Use* concept to reveal touch traces on handles in public transport. The design intention was to provide users with the choice to avoid touching the same spot as others had recently done before. By this, we contextualized the interface to raise awareness of potential smear infection risks. In comparison to the material traces designs of the previous project [P6], the touched areas were only visible through differently colored lights until the handle was self-cleaned. All participants who indicated using handles in public transport (n=51/52) would change their touch behavior based on the revealed touch traces. In line with the previous paper [P6], this project confirms

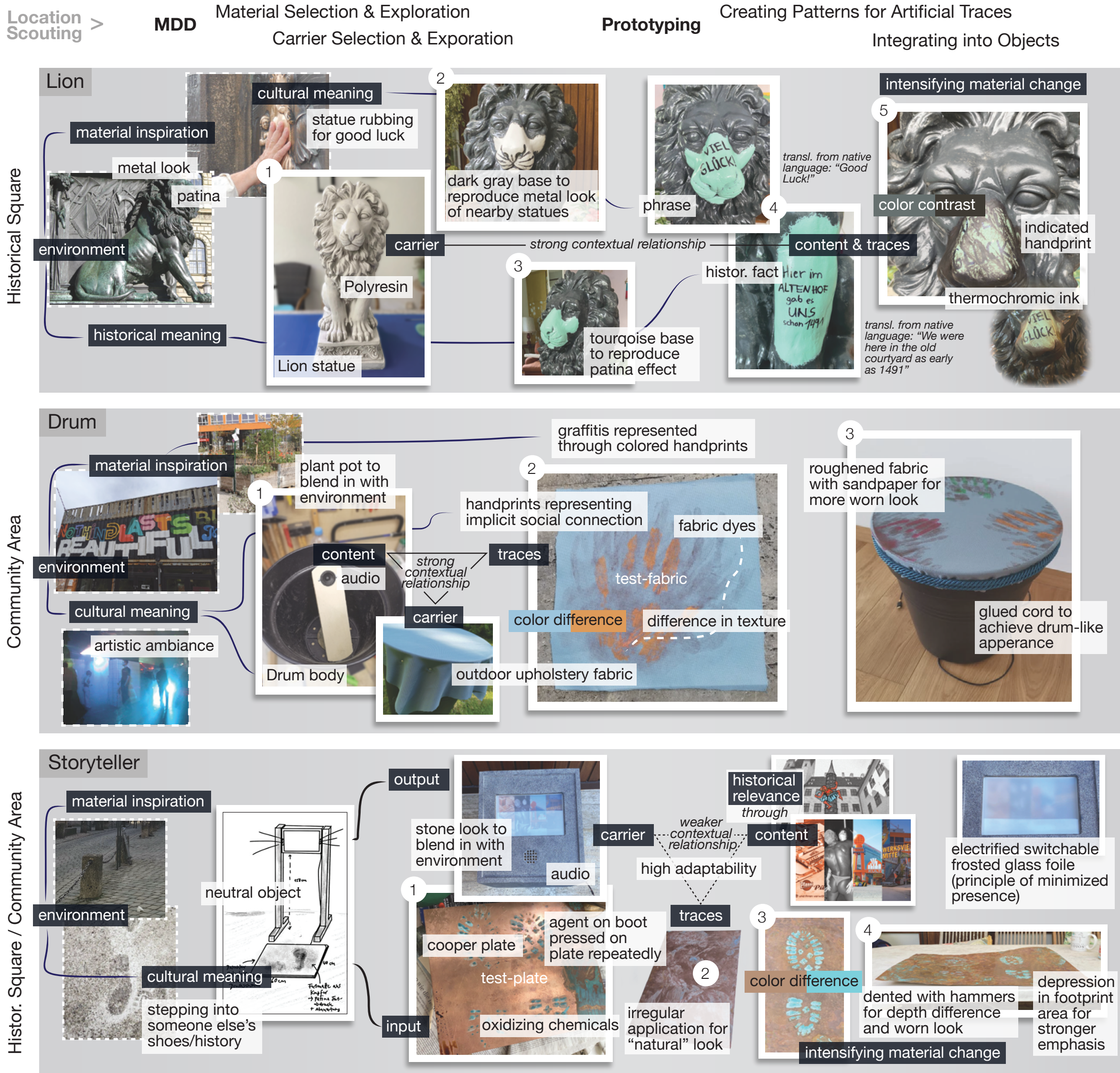


Figure 3.2: The *research in* and *through design* approach for each interface as presented in [P6], including inspirations from the place analyses and the considered contextualization perspectives. Textual annotations relating to specific design characteristics and choices pertaining to the interfaces are encoded through white background color; annotations of black background color indicate the conceptual implications of designing *Traces in Use* interfaces.

the traces' characteristic of revealing relations between different entities [178] and triggering strong sense- and meaning-making in users.

3.3.2 Empirical Evaluation and Design of VR Traces

Social connectedness in VR can be supported by allowing users to make environmental changes and reflect them back to users [106, 147]. Additionally to related work and previous findings, this motivated us to explore the *Traces in Use* concept for social VRs.

We first replicated PR traces in VR (see Figure 3.3, left) and compared in a between-subject study (N=20) how users interpreted them [P3]. Our Bayesian statistics indicated that it is almost five times as likely that there is no difference in the perception of PR to VR traces. In the within-subject follow-up study (N=26), we tested the traces' effect on social presence and social awareness. We tested four types of PR traces in VR, comparing a VR room with and one without traces (see the room with traces in Figure 3.3, right). We could not find any significant differences between the traces' types [16]. Yet, social presence and time spent were significantly higher in the room with traces. The qualitative feedback also showed that the traces triggered emotions in diverging directions. The majority perceived the VR with traces more *"homely"*, *"inviting"*, and *"authentic"*. In contrast, six participants also worried about what had happened to cause the traces or were reminded of unpleasant PR duties. Both studies show that the traces have a similar effect in PR and VR. However, by transferring PR traces one-to-one into VR, we ignored natural VR characteristics such as its flexibility and the different design opportunities that it offers.

In the following study, we considered that in VR everything has to be implemented and designed. This also questioned what "natural" VR traces are that comply with being recognizable, meaningful, and can seamlessly be embedded into VRs. Accordingly, in [P9], we explored visualizing and embedding previous players' heartbeats into a single-user VR gaming environment to increase social connectedness implicitly. The heartbeats pulsated and were spatially and temporally embedded according to the previous player's movement through the VR. This automatically turned the visualizations into ephemeral representations of the former players. In a within-subject study (N=34), we compared five game scenarios, including four visualizations of the heartbeat data and one baseline condition without visualizations. For the visualizations, we altered between single and multi-player data visualizations paired with two well-known heartbeat visualization styles, ECG lines [55, 125], and heart icons [62]. All but one visualization significantly increased social connectedness without significantly impacting the gaming experience. For about half of the participants, the visualizations contextualized the environment and the game and assisted players in finding the next cues. However, the qualitative feedback revealed challenges for future work regarding the traces' scalability and their embedding into VR while assuring the traces' understandability. Or what privacy and security issues might derive from sharing such personal yet anonymized data?

3.3.3 Extending the Concept into AR

Following the *Traces in Use* concept exploration in VR, we also tested the concept in AR [P4]. For this, we developed an AR application for mobile phones in Android studio that allowed users to anchor AR social media posts location-based. We defined the posts as AR traces contextualizing the places regarding former activities and social encounters in an environment. We tested the app in a two-phase field study (N=17), first with content generators familiar with

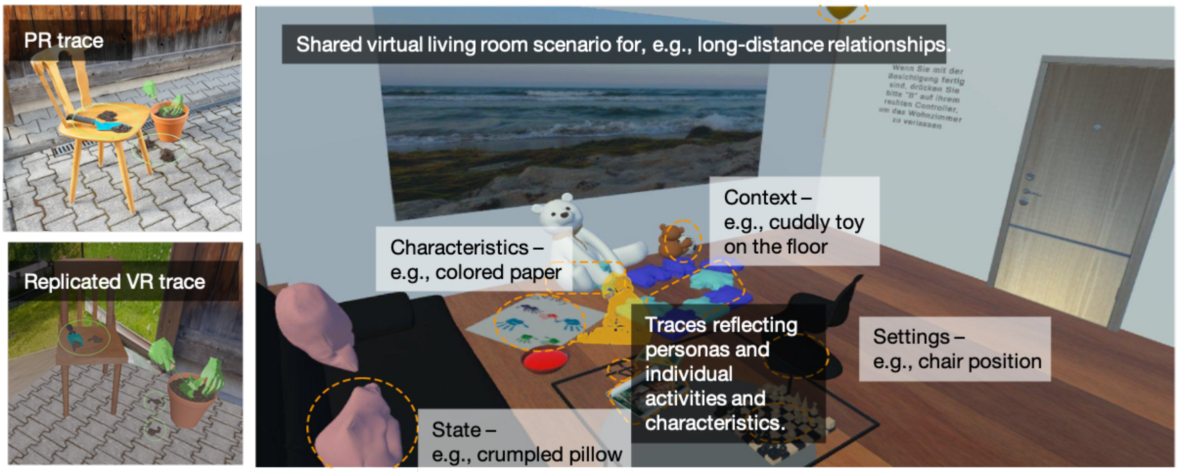


Figure 3.3: We replicated PR traces in VR: Left) Comparing the traces' effect in PR to VR. Right) Testing the traces for social presence and awareness as presented in [P3]. The black background highlights the conceptual implications and the white background the traces types.

the environment followed by retrievers who were mainly novel to the area. We applied a walking & talking method [195] and the Plutchnik Wheel [169] to assess participants' emotional connectedness to the different locations. Retrievers tested the functional app with real-time content sharing and retrieving. The results confirmed significantly increased place identity [23] for novel users. Consequently, the AR traces supported meaningful asynchronous interactions in shared environments. Compared to the PR traces, we did not fully assess the AR traces context-specific naturalness. Yet, they are only visible to interested app users, which makes them comply with the need for unobtrusive interface embedding. At the same time, this also creates exclusive content accessibility [127, 165]. While the AR "material" was contextualized to the respective places, it faces similar challenges as VR traces regarding, for example, their scalability. With increasing location-based posts, the content would overlap without changing or degrading like the PR traces. This can further clutter users' views and lead to movement risks [42]. Consequently, applying the concept in AR seems to require a better connection between AR and PR than in our exploration and a topic for future work.

3.3.4 Summary & Future Work

The different research projects confirm the *Traces in Use* design concept to contextualize interfaces and environments for meaningful interactive XR experiences (**RQ3**). They identified differences in identifying and designing natural, unobtrusive, and recognizable traces for the different realities. To that end, making the trace design requires considering the technological requirements and limitations to define what context-specific natural traces are that are additionally feasible for implementation. Applying the concept in AR or VR entails other challenges and complexities than PR contexts. For example, it is the designers' responsibility to make design decisions on the users' behalf. This includes, for example, the lifetime of a trace or how comprehensible it is communicated to the user. Furthermore, the PR studies presented in [P6] triggered users understanding of the places' historical significance. Based on the current results, the traces seem to increase the perceived authenticity of a place [P3, P6]. However, it is an outstanding research question whether the *Traces in Use* concept could support the same effect in VR or AR environments. Nonetheless, these studies also confirm the concept's persisting quality of contextualizing an interface or an environment independent of the reality. This also validates the concept definition presented in STEP II. As such, the concept contributes to designing meaningful interactions in different XR contexts and shared environments. Yet, future work has to test the concept in long-term use and how the results might impact the making of the trace designs.

4
DISCUSSION

Chapter three presented 13 research papers contributing to developing and evaluating approaches for meaningful human-environment interaction. Here, I first reflect on the overall research approach along the guiding questions presented in the introduction, **Q1**) how we can design embedded and meaningful interfaces in shared environments, **Q2**) how we can conceptualize traces of into *Traces in Use*, and **Q3**) how the concept might vary depending on the reality. Afterward, I focus the discussion on the *Traces in Use* design concept as its development and evaluation is the main contribution of this thesis. This includes reflecting on the concept in the context of creating meaningful human-environment interactions in different XR environments.

4.1 Critical Reflection on the Research Approach

Various decisions drive the overall research approach presented in this thesis, influencing its outcome. This includes, for example, focusing exclusively on physically and spatially embedded interfaces in STEP I and II [P1, P5, P11, P12], or designing for specific meaningful interaction components. By deciding to research approaches for embedding interfaces **(Q1)**, the thesis focuses on technology that is interwoven into our everyday context [P7, P11, 212] and environments [P6, P12, P13]. I approached **Q1** by designing from two perspectives following Stephanidis et al. [199]'s statement of calmly embedding interfaces *"either physically, through integration in the environment, or mentally from our perception"*. This also led to enhancing material and carrier qualities, such as making concrete capacitive or translucent [P11, P12] instead of introducing new devices to the environments, such as a pervasive display. Pervasive displays can be perceived as context-specific natural for a public place, c.f., [4, 47, 207], following our definition in [P7]. Yet, by choosing historical places [P1, P5, P12] instead of, for example, a shopping mall as initial contexts, this thesis moved in a different direction. With the selected approach, the thesis contributes to emphasizing a place's atmosphere and supports customizing designs to specific and sensitive environments.

Similarly, the thesis conceptualizes and evaluates traces for design **(Q2)** depending on a specific context and as part of a carrier in all but one case ([P11]). This causes a bias and limits the results regarding the traces' effect on contextualizing interfaces. Alternatively, I could have explored other means to trigger meaning-making. Wouters et al. [221], for example, present an approach to socially connecting users through participatory design via public display interaction. By exploring traces, this work contributes to implicitly triggering sense- and meaning-making without any direct or synchronous user interaction, as shown in [P3, P6, P11]. *Traces in Use* designs increase an interface's level of contextualization by adding materials experience design knowledge to the process. The work additionally extends the contextualization perspectives by Vande Moere and Wouters [205] by integrating a material perspective [P6]. Further, following a context-driven approach highlights the role of the material-place relationship in human-environment interaction and the influence of a place's socio-cultural and physical and spatial conditions on the interaction experience [P1, P2, P6, P10, P12]. This thesis also shows that the semantic meaning of *Traces in Use* interfaces and their making strategies are determined by the context they are designed for [P3, P6, P11] and, thus, have to be evaluated in it despite the potential bias.

Exploring the *Traces in Use* design concept in different realities (**Q3**) challenges the approach of looking at natural traces of use to guide the design process. There are no "natural" traces in AR or VR. On the one hand, this makes it harder to define what type of traces should be considered and how they should be designed. On the other hand, this also provides more flexibility for designers. In [P3], we transfer PR traces into VR. While the traces increase the VR environment's meaningfulness, the experience partly does not meet users' expectations of a "natural" VR environment. This reveals limitations in the approach by contextualizing the VR environment with virtual representations of physical reality traces instead of directly designing VR-specific traces [P9]. STEP III summarizes other technological and environmental differences [P3, P4, P8, P9] essential for the design process. Further, VR enables greater environmental control because VR enables the reduction of external biases and allows more quantifiable measurements than PR environments. However, VR and AR also require defining more details of the *Traces in Use* design because they lack the natural trace development happening over time in the PR. The exploration in [P9] contributes an approach to designing and embedding VR-specific *Traces in Use* into the environment. In that paper, the *Traces in Use* are embedded without a carrier. This requires generating new understandable, and meaningful *Traces in Use* designs directly related to the environment to reflect the socio-spatial meaning that natural PR traces have through their manifestation in the carrier. Altogether, the applied approach reveals divergences when designing *Traces in Use* in different XR environments and contributes with approaches to create *Traces in Use* interfaces without a "natural" counterpart.

4.2 From Environmental Features to an Interaction Design Concept

The thesis comprised the whole development and evaluation process of the *Traces in Use* design concept, including the initial context explorations [P1, P5, P12]. The concept is grounded on the natural trace characteristics of embodying and manifesting intangible socio-cultural values and meanings [103, 179, 215, 216]. *Traces in Use* designs differ from natural traces by being structured and purposefully applied, and a clear trace shape with little surrounding noise or distraction [P10, P11]. When designing *Traces in Use* interfaces, this also means considering the natural trace development generated over time and use, including weathering, so that the natural traces of use do not interfere with the *Traces in Use* designs. The concept supports calmly contextualizing interfaces for shared environments and communicating places' history, and contemporary usage [P6]. With this, *Traces in Use* contribute to counteracting the problem of smart environments being at risk of losing the original authenticity and identity of cities [188]. Furthermore, the concept can help to communicate a temporal course, and transience, which is currently an ongoing challenge in PR [186], AR [112], and VR [106]. The *Traces in Use* can mitigate the challenge and contribute to fostering building meaningful user-place relationships [P4, P6]. This opens opportunities for urban architects and city planners to connect smart environments with the local identity contextualizing the environment with the *Traces in Use* design concept.

Furthermore, the *Traces in Use* design concept contributes to the design theory of contextualizing interfaces and revealing entanglements [178, 182]. Additionally, it helps users to become aware of dynamics and connections that exceed the individual and situational user experience. In [P6], I position the concept in the intermediate space between generalizable theory and the situational knowledge of individual design projects, which classifies it as a strong design concept[1] according to Höök and Löwgren [93]. This separates the concept practically and theoretically from natural traces of use and positions it within HCI research.

In an application context, *Traces in Use* interfaces are subject to users' subjective and volatile meaning-making, which changes over time and experience [148]. For example, hygiene and cleanliness are currently much more prominent due to the COVID-19 pandemic [101, 141, 214] and can lead to concerns when interacting with *Traces in Use* interfaces [P3, P6, P11]. Thus, this volatile meaning-making can challenge the usage and meaning of, particularly, physical *Traces in Use* interfaces. In contrast, AR and VR offer more flexibility [P4], which enables adapting *Traces in Use* interfaces according to potential changes.

The above-mentioned dynamics offer new opportunities for research and industry. For example, the *Traces in Use* design on a public transport handle [P8] revealed touch traces as long as the smear infection risk persisted. Such an interface could be handy for similar situations, such as door handles in public bathrooms or touch buttons in an elevator. The advantage of the *Traces in Use* design is that it neither prevents users from interacting nor tells them what meaning to make of it. In contrast, it increases awareness to make a more informed decision and triggers users to reflect and make meaning depending on their personal background and experiences. The same accounts for *Traces in Use* in other realities. The VR game paper [P9], for example, highlights the traces' effect of triggering collaborative or competitive meaning depending on how players integrate or compare them to their personal performance.

As *Traces in Use* are detached from their generators, they allow only limited meaning-making and understanding. Yet, this also means that they keep the person anonymous who generated them. In VR, this provides opportunities for social VR and game designers to, for example, trigger the sensation of co-location and social connectedness while protecting users' identities [P9, 197]. Consequently, the *Traces in Use* design concept implicitly supports increasing meaning for asynchronous and anonymous social interactions.

[1] A strong design concept is a form of intermediary knowledge that results from exploratory design research, where the findings are often situational but can generate knowledge beyond the specific situation [61, 93, 223].

4.3 Revealing Entanglements in XR Environments

Providing meaningful human-environment interaction is a design goal in PR, AR, and VR [199, 200]. Yet, the thesis shows differences between the realities regarding the *Traces in Use*' making, type, and trustworthiness [P3]. These differences require taking a step back and understanding the context-specific socio-cultural dynamics, practices, and relationships when designing *Traces in Use*. This also reflects in the traces' form, lifetime, and materiality that heavily diverged in the empirical evaluations [P3, P4, P6, P8, P9]. For example, the AR- and VR-specific traces are intangible and positioned mid-air because there is no restriction due to gravity in contrast to the PR interfaces. Further, the presented VR-specific traces are based on measured ECG data contextualized with the user's performance data [P9]. Accordingly, we reveal entanglements through shared visualized interoceptive data[2] to support users' feeling of social connectedness [P9]. Consequently, the XR *Traces in Use* design space comprises many more possibilities to reveal entanglements and provide meaningful interactions, strengthening the concept's contribution to human-environment interaction. This also extends design opportunities for human-environment interaction by revealing so far invisible data traces.

The aforementioned differences show that the empirical *Traces in Use* concept evaluations in STEP III are not comparable [P3, P4, P6, P8, P9]. Yet, in each project, the *Traces in Use* reveal the entanglements between people, practices, materials, and places [P3, P4, P6, P9]. Similarly, they trigger users' sense- and meaning-making independently of the reality. Hence, the applied concept has a comparable effect on the user experience in the different realities.

Furthermore, the thesis shows that the concept can support place-making [P3, P4, P6] in PR, VR, and AR by implicitly communicating intangible social and cultural meanings. This shows in, for example, users copying previous users' movements and behaviors when interacting with *Traces in Use* interfaces such as the Lion statue in [P6]. A similar effect also applies to traces that can serve as spatial navigation, such as the ECG traces in [P9] that accumulated at common points of interest. We explain this effect in [P6] as a detached honeypot effect [220], in which users want to mimic their interaction with how others interacted with the interface. Applying the *Traces in Use* concept invites to engage with surroundings [P3, P6], which increases the attachment [P4] and contributes to place-making and the user-place relationship.

Altogether, the *Traces in Use* concept application and evaluation in the different realities yield differences in the traces' making and materiality but seem to align regarding their conceptual and semantic meaning. Thus, contextualized *Traces in Use* interfaces incorporate the ability to reveal entanglements and support designing for meaningful relations and interaction in varying XR environments.

[2] Interoceptive data are linked to internal body sensations that additionally enables emotion processing, such as heartbeat, nervous system, etc. Such data can normally not be perceived by others and only partially by oneself [58, 65].

5
FUTURE WORK

To shape who we want to be in this world, we should be designing meaningful relations, not user experiences.

– C. Frauenberger [61]

Figure 5.1: **Speculative Vision of Smart Cities with *Traces in Use*.** The city is a place for the people, their social life, and their culture. Places are shared with autonomous robots and other beings. Everyone seems aware and connected to the place and each other. The digital has merged into the physical, and the physical into the virtual, showing the implicit traces of the contemporary and past generations. I can see how everything belongs together and what special character the city has. © Seyda Yildiz

The thesis contributes to creating meaningful human-environment interactions. With this, the work tackles a subject of the *HCI Grand Challenges* [199] and contributes to a better understanding of contextualizing interfaces [205, 219] that foster meaningful engagement with one's surroundings [204] while avoiding information overload and distraction. Further, this work includes insights about designing for place-making [50] and socio-cultural connectedness [148, 186] in three realities and six different environments. At the same time, the work also reveals gaps in the approach and future research potential, which I address here:

First, all research projects were conducted under Western-European conditions and perspectives. This accounts for the public places explored in STEP I and III and my choices of what entanglements the *Traces in Use* interfaces should reveal to users. Thus, the work has a cultural and subjective bias, which requires further concept exploration in other cultural contexts conducted by other researchers. Future work could compare the results for different cultural contexts or explore the *Traces in Use* potential to connect people of different cultural backgrounds within a shared space.

Second, the thesis focused on meaningful human traces in one-time interaction scenarios. Yet, shared environments can be used by other beings such as robots [92], animals [39, 59], or virtual agents [77]. This raises questions about how other beings' traces could and should be considered in the design. The traces also develop and increase in quantity. This questions how to scale *Traces in Use* designs, particularly over long-term use and when including multiple being's traces. Future HCI research could explore customizing what activity data, e.g., physical material changes in the environment or users' physiological data, is tracked and turned into *Traces in Use* interfaces for meaningful interactions. In the context of shared environments, this also means exploring the involvement and control that other beings would have. Thus, a future project could research how to provide customized meaningful *Traces in Use* in parallel to multiple users in a shared environment.

Third, future work needs to research ethical regulations. For example, one of the requirements identified in [P3] is to design authentic traces that reflect what or who generated them. This is because artificially created traces can also be misused to create a feeling of security or to nudge users to interact in a certain way. Using traces in such ways can derive from good intentions but deprives users of autonomous decision-making. Another ethical concern is that digital or virtual traces are tracked and created by design. This questions, for example, how we keep users informed about the tracking without overwhelming them. Similarly, how much control should users have over the monitoring? While many might respond to the last question with *"100%"*, providing this level of control is complex. In our work [P9], users knew about the data recording and processing but were not involved in the design process of turning their data into traces. In future work, researchers should explore means to indicate a trace's origins and potential sharing regulations.

Fourth, the thesis developed and explored the *Traces in Use* concept for shared PR, AR, and VR environments. Yet, the different realities can also merge into MR [105, 194], which is challenged by providing smooth transitions along the reality-virtuality continuum[1] [149]. Future work could research the traces' potential to support a smooth transition. For example, in this direction, we explored them as memory cues [135]. This includes exploring the shift of the traces' materiality along the continuum and translating VR- or AR-specific traces into PR traces and vice versa to support users' connection on both sides of and within the spectrum.

The thesis introduces new research questions and opportunities concerning *Traces in Use* and smart interactive environments, in general. Furthermore, the work shows that the relatively "old" notion of traces remains a relevant topic for HCI and human-environment interaction with a huge and mainly unexplored design space for MR and XR traces.

[1]The reality-virtuality continuum describes the transition spectrum between physical and virtual reality for technologies and interfaces [149, 193].

Statement of Contributions

The research within this thesis would not have been possible without my supervisor, colleagues, and the students I supervised. The table below separates my contribution from others' to the included papers.

Paper	My Contribution	Co-author(s) Contribution
[P1]	I was the leading author, conducted the onsite and the data analysis.	A. Butz provided feedback on the paper.
[P2]	I was the leading author and coordinator.	E. Economidou, I.Parschivoiu, and T. Doering contributed to the paper writing.
[P3]	I was the leading author, conducted the interviews, developed the framework and the study design, did the statistical and thematic analyses, and did most of the paper writing.	C. George conducted the thematic analysis with me, supported the study design, and contributed to the paper writing. A. Butz gave feedback on the paper.
[P4]	I was the main supervisor, and leading author, defined the study design, supported the onsite data gathering and did the analysis.	I. Graf von Silva-Tarouca was the student who built the prototype and mainly conducted the study. R. Welsch co-supervised the student and gave feedback on the paper.
[P5]	I was the leading author, co-developed the concepts, and co-conducted the analysis.	F. Hild is a master student who conducted the interviews and co-developed the concepts and the analysis. M. Obaid co-supervised the student and provided feedback on the paper.
[P6]	I was the leading author, developed the framework, conducted the interviews and all data evaluations, and provided the study design.	M. Hoggenmueller and C. George contributed to the writing. L. Bekker and S. Sridharan were two bachelor students who prototyped the interfaces and conducted onsite studies. A. Butz gave feedback on the paper.
[P7]	I was the leading author and co-conducted the literature survey.	J. Li conducted the literature study with me, created 2 of the figures, and supported the paper writing. S. Mayer and A. Butz provided feedback on the paper.

[P8]	I was the leading author and main supervisor.	Y. Li co-supervised the student H. Geiger. H. built the prototype and conducted the online study. A. Butz gave feedback on the paper.
[P9]	I was the leading author, created the study design, and conducted the design workshop and qualitative data analysis.	F. Mueller and F. Chiossi co-supervised the student and supported the study design T. Benga with me. F. Mueller conducted the statistical analysis and F. Chiossi the ECG data evaluation. T. Benga developed the VR escape room and conducted the user study. A. Butz gave feedback on the paper.
[P10]	I was the leading author, conducted the focus group and the data collection and analysis.	B. Rossmy co-developed the concept with me, contributed to the data analysis, supported the writing, and provided two visualizations for the pictorial. F. Bemman implemented the web tool to run the study. A. Butz gave feedback on the paper.
[P11]	I was the leading author, co-created the prototypes, and conducted both studies (elicitation and bodystorming) and most of the evaluation.	B. Rossmy co-developed the concept and the making strategies with me, contributed to the data analysis, and supported the paper writing. A. Butz gave feedback on the paper.
[P12]	I was the leading author. This included co-conducting the literature survey, making the prototypes, and running the field study and the analysis.	C. Schneegass co-conducting the literature survey and supported the paper writing. R. Welsch supported the paper writing and the statistical analysis. A. Butz gave feedback on the paper.
[P13]	I was co-author, providing a concept discussion, and contributing to the related work and discussion.	A. Wiethoff was the leading author and project leader. All other authors equally contributed to the paper writing.

Table 5.1: Clarification of my own and others' contributions to the projects included in this thesis.

My Publications

[P1] Hirsch, L. and Butz, A. (2021). "Blend in or Pop Out? Designing an Embedded Interface for a Historical Cemetery." In: *INTERACT*. DOI: 10.1007/978-3-030-85613-7_40.

[P2] Hirsch, L., Economidou, E., Paraschivoiu, I., and Döring, T. (2022a). "Material Meets the City: A Materials Experience Perspective on Urban Interaction Design." In: *Interactions* 29.1, pp. 58–63. DOI: 10.1145/3501358.

[P3] Hirsch, L., George, C., and Butz, A. (2022b). "Traces in Virtual Environments: A Framework and Exploration to Conceptualize the Design of Social Virtual Environments." In: *Proceedings of the 2022 ISMAR*. Vol. 28. ISMAR '22. IEEE. DOI: 10.1109/TVCG.2022.3203092.

[P4] Hirsch, L., Graf von Silva-Tarouca, I., and Welsch, R. (2022c). "Increasing Socio-Spatial Connectedness Among Students: A Location-Based AR Social Media Network Approach." In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA '22. Association for Computing Machinery. DOI: 10.1145/3491101.3519681.

[P5] Hirsch, L., Hild, F., and Obaid, M. (2022d). "Design Recommendations for Historical Cemeteries Using Speculative Design." In: *Proceedings of the 25th International Academic Mindtrek Conference*. Academic Mindtrek '22. Association for Computing Machinery, pp. 147–157. DOI: 10.1145/3569219.3569378.

[P6] Hirsch, L., Hoggenmueller, M., George, C., Bekker, L., Sriddharan, S., and Butz, A. (2023a). "The Traces in Use Design Concept." In: *currently under submission at TOCHI*. DOI: 10.1145/tbd.

[P7] Hirsch, L., Li, J., Mayer, S., and Butz, A. (2022e). "A Survey of Natural Design for Interaction." In: *Proceedings of Mensch Und Computer 2022*. MuC '22. Association for Computing Machinery, pp. 240–254. DOI: 10.1145/3543758.3543773.

[P8] Hirsch, L., Li, Y., Geiger, H., and Butz, A. (2021a). "Safe-to-Touch: Tracking Touched Areas in Public Transport." In: *IFIP TC13 International Conference on Human-Computer Interaction*. DOI: 10.1007/978-3-030-85607-6_63.

[P9] Hirsch, L., Mueller, F., Chiossi, F., Benga, T., and Butz, A. (2023b). "My Heart Will Go On: Implicitly Increasing Social Connectedness By Visualizing Asynchronous Players' Heartbeats in VR Games." In: *currently under submission at CHI Play'23*. DOI: 10.1145/3611057.

[P10] Hirsch, L., Rossmy, B., Bemmann, F., and Butz, A. (2020). "Affordances Based on Traces of Use in Urban Environments." In: *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '20. Association for Computing Machinery, pp. 729–742. DOI: 10.1145/3374920.3375007.

[P11] Hirsch, L., Rossmy, B., and Butz, A. (2021b). "Shaping Concrete for Interaction." In: *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '21. Association for Computing Machinery. DOI: 10.1145/3430524.3440625.

[P12] Hirsch, L., Schneegass, C., Welsch, R., and Butz, A. (2021c). "To See or Not to See: Exploring Inattentional Blindness for the Design of Unobtrusive Interfaces in Shared Public Places." In: *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5.1. DOI: 10.1145/3448123.

[P13] Wiethoff, A., Hoggenmueller, M., Rossmy, B., Hirsch, L., Hespanhol, L., and Tomitsch, M. (2021). "A Media Architecture Approach for Designing the Next Generation of Urban Interfaces." In: 48, pp. 9–32. DOI: 10.55612/s-5002-048-001.

References

[1] Alawadi, K. (2017). "Place attachment as a motivation for community preservation: The demise of an old, bustling, Dubai community." In: *Urban Studies* 54.13, pp. 2973–2997. DOI: 10.1177/0042098016664690.

[2] Alencar, T., Barbosa, M., Machado, L., Neris, L., and Neris, V. (2018). "Considering the Diversity of Users in the Development of a Flexible Bus Stop." In: *Proceedings of the 17th Brazilian Symposium on Human Factors in Computing Systems*. IHC 2018. Association for Computing Machinery. DOI: 10.1145/3274192.3274205.

[3] Alexander, C., Ishikawa, S., and Silverstein, M. (1977). A Pattern Language: Towns, Buildings, Construction. Oxford University Press.

[4] Alt, F., Bulling, A., Mecke, L., and Buschek, D. (2016). "Attention, please!: Comparing Features for Measuring Audience Attention Towards Pervasive Displays." In: *ACM Conference on Designing Interactive Systems*. Association for Computing Machinery, pp. 823–828. DOI: 10.1145/2901790.2901897.

[5] Altarriba Bertran, F., Duval, J., Bisbe Armengol, L., Chen, I., Dong, V., Dastoor, B., Altarriba Bertran, A., and Isbister, K. (2021). "A Catalog of Speculative Playful Urban Technology Ideas: Exploring the Playful Potential of Smart Cities." In: *Proceedings of the 24th International Academic Mindtrek Conference*. Academic Mindtrek '21. Association for Computing Machinery, pp. 60–71. DOI: 10.1145/3464327.3464374.

[6] Alves, S. (2014). "Affordances of Historic Urban Landscapes: An Ecological Understanding of Human Interaction with the Past." In: *European Spatial Research and Policy* 21. DOI: 10.1515/esrp-2015-0002.

[7] Amandine Junot, Y. P. and Fenoulliet, F. (2018). "Place attachment influence on human well-being and general pro-environmental behaviors." In: *Journal of Theoretical Social Psychology* 2 (2), pp. 49–57.

[8] Ambrosino, M. A., Andriessen, J., Annunziata, V., De Santo, M., Luciano, C., Pardijs, M., Pirozzi, D., and Santangelo, G. (2018). "Protection and Preservation of Campania Cultural Heritage Engaging Local Communities via the Use of Open Data." In: *Proceedings of the 19th Annual International Conference on Digital Government Research: Governance in the Data Age*. dg.o '18. Association for Computing Machinery. DOI: 10.1145/3209281.3209347.

[9] André, P., Schraefel, M. C., Dix, A., and White, R. W. (2011). "Expressing Well-Being Online: Towards Self-Reflection and Social Awareness." In: *Proceedings of the 2011 IConference*. iConference '11. Association for Computing Machinery, pp. 114–121. DOI: 10.1145/1940761.1940777.

[10] Araujo de Aguiar, C. H. (2019). "TransFORM - A Cyber-Physical Artefact Augmenting Social Interaction in Residual Public Spaces." In: TEI '19. Association for Computing Machinery, pp. 745–748. DOI: 10.1145/3294109.3302959.

[11] Aravot, I. (2002). "Back to Phenomenological Placemaking." In: *Journal of Urban Design* 7.2, pp. 201–212. DOI: 10.1080/1357480022000012230.

[12] Badawy, A., Ferrara, E., and Lerman, K. (2018). “Analyzing the Digital Traces of Political Manipulation: The 2016 Russian Interference Twitter Campaign.” In: *Proceedings of the 2018 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining*. ASONAM ’18. IEEE Press, pp. 258–265.

[13] Bakker, S., Hausen, D., and Selker, T. (2016). “Introduction: Framing Peripheral Interaction.” In: *Peripheral Interaction*. Springer. Chap. 1, p. 6. DOI: 10.1007/978-3-319-29523-7_1.

[14] Bandarin, F. and Oers, R. van (2012). The Historic Urban Landscape Managing heritage in an urban century. 1st ed. Wiley-Blackwell, p. XIII.

[15] Baumann, K., Stokes, B., Bar, F., and Caldwell, B. (2017). “Infrastructures of the Imagination: Community Design for Speculative Urban Technologies.” In: *Proceedings of the 8th International Conference on Communities and Technologies*. C&T ’17. Association for Computing Machinery, pp. 266–269. DOI: 10.1145/3083671.3083700.

[16] Baxter, W., Aurisicchio, M., and Childs, P. (2016). “Materials, use and contaminated interaction.” In: *Materials & Design* 90. DOI: 10.1016/j.matdes.2015.04.019.

[17] Bidwell, N. and Browing, D. (2010). “ursuing genius loci: interaction design and natural places.” In: *Pers Ubiquit Comput* 14, pp. 15–30. DOI: 10.1007/s00779-009-0217-8.

[18] Biedermann, P. and Vande Moere, A. (2021). “A Critical Review of How Public Display Interfaces Facilitate Placemaking.” In: *Media Architecture Biennale 20*. MAB20. Association for Computing Machinery, pp. 170–181. DOI: 10.1145/3469410.3469427.

[19] Bielfeldt, R. (2018). “Candelabrus and Trimalchio: Embodied Histories of Roman Lampstands and their Slaves.” In: *Art History* 41.3, pp. 420–443. DOI: https://doi.org/10.1111/1467-8365.12382.

[20] Bielfeldt, R. (2014). Ding und Mensch in der Antike. Vol. 16. Universitätsverlag Winter GmbH Heidelberg.

[21] Bødker, S. (2006). “When Second Wave HCI Meets Third Wave Challenges.” In: *Proceedings of the 4th Nordic Conference on Human-Computer Interaction: Changing Roles*. NordiCHI ’06. Association for Computing Machinery, pp. 1–8. DOI: 10.1145/1182475.1182476.

[22] Bødker, S. and Christiansen, E. (2004). “Designing for Ephemerality and Prototypicality.” In: *Proceedings of the 5th Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*. DIS ’04. Association for Computing Machinery, pp. 255–260. DOI: 10.1145/1013115.1013151.

[23] Boley, B. B., Strzelecka, M., Yeager, E. P., Ribeiro, M. A., Aleshinloye, K. D., Woosnam, K. M., and Mimbs, B. P. (2021). “Measuring place attachment with the Abbreviated Place Attachment Scale (APAS).” In: *Journal of Environmental Psychology* 74, p. 101577. DOI: https://doi.org/10.1016/j.jenvp.2021.101577.

[24] Borgmann, A. (1984). “Technology and the Character of Contemporary Life: A Philosophical Inquiry.” In: The University of Chiago Press.

[25] Bosch, T. (2012). Sci-Fi Writer Bruce Sterling Explains the Intriguing New Concept of Design Fiction. URL: https://slate.com/technology/2012/03/bruce-sterling-on-design-fictions.html.

[26] Bowman, D. A., McMahan, R. P., and Ragan, E. D. (2012). "Questioning Naturalism in 3D User Interfaces." In: *Commun. ACM* 55.9, pp. 78–88. DOI: 10.1145/2330667.2330687.

[27] Brand, S. (1994). How Buildings Learn: What Happens After They're Built. Viking.

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

[29] Brunette, K., Eisenstadt, M., Pukinskis, E., and Ryan, W. (2005). "Meeteetse: Social Well-Being through Place Attachment." In: *CHI '05 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '05. Association for Computing Machinery, pp. 2065–2069. DOI: 10.1145/1056808.1057100.

[30] Butz, A. (2010). "User Interfaces and HCI for Ambient Intelligence and Smart Environments." In: *Handbook of Ambient Intelligence and Smart Environments*. Springer US, pp. 535–558. DOI: 10.1007/978-0-387-93808-0_20.

[31] Cacioppo, J. T. and Patrick, W. (2008). Loneliness: Human Nature and the Need for Social Connectedness. Norton.

[32] Caldwell, G. A., Guaralda, M., Donovan, J., and Rittenbruch, M. (2016). "The InstaBooth: Making Common Ground for Media Architectural Design." In: *Proceedings of the 3rd Conference on Media Architecture Biennale*. MAB. Association for Computing Machinery. DOI: 10.1145/2946803.2946806.

[33] Caraban, A., Karapanos, E., Gonçalves, D., and Campos, P. (2019). "23 Ways to Nudge: A Review of Technology-Mediated Nudging in Human-Computer Interaction." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Association for Computing Machinery. DOI: 10.1145/3290605.3300733.

[34] Case, A. (2015). Calm technology : principles and patterns for non-intrusive design. 1st ed. O'Reilly Media, Inc., pp. 15–17.

[35] Cater, K., Chalmers, A., and Ledda, P. (2002). "Selective Quality Rendering by Exploiting Human Inattentional Blindness: Looking but Not Seeing." In: *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*. VRST '02. Association for Computing Machinery, pp. 17–24. DOI: 10.1145/585740.585744.

[36] Chalmers, A., Debattista, K., Sundstedt, V., Longhurst, P. W., and Gillibrand, R. (2006). "Rendering on Demand." In: *EGPGV*, pp. 9–17. DOI: https://doi.org/10.2312/EGPGV/EGPGV06/009-017.

[37] Ciolfi, L. and Petrelli, D. (2015). "Studying a Community of Volunteers at a Historic Cemetery to Inspire Interaction Concepts." In: *Proceedings of the 7th International Conference on Communities and Technologies*. C&T '15. Association for Computing Machinery, pp. 139–148. DOI: 10.1145/2768545.2768547.

[38] Claes, S. and Vande Moere, A. (2013). "Street Infographics: Raising Awareness of Local Issues through a Situated Urban Visualization." In: *Proceedings of the 2nd ACM International Symposium on Pervasive Displays*. PerDis '13. Association for Computing Machinery, pp. 133–138. DOI: 10.1145/2491568.2491597.

[39] Clarke, R., Heitlinger, S., Light, A., Forlano, L., Foth, M., and DiSalvo, C. (2019). "More-than-Human Participation: Design for Sustainable Smart City Futures." In: *Interactions* 26.3, pp. 60–63. DOI: 10.1145/3319075.

[40] Cohen, S. (1978). "Environmental Load and the Allocation of Attention in A. Baum, JE Singer, and S. Valins (eds.)" In: *Advances in Environmental Psychology Volume 1: The Urban Environment*. John Wiley & Sons Inc, pp. 1–29.

[41] Colley, A., Hakala, L., Harjuniemi, E., Jarusriboonchai, P., Müller, H., and Häkkilä, J. (2019). "Exploring the Design Space of Electrochromic Displays." In: *Proceedings of the 8th ACM International Symposium on Pervasive Displays*. PerDis '19. Association for Computing Machinery. DOI: 10.1145/3321335.3329687.

[42] Colley, A., Thebault-Spieker, J., Lin, A. Y., Degraen, D., Fischman, B., Häkkilä, J., Kuehl, K., Nisi, V., Nunes, N. J., Wenig, N., Wenig, D., Hecht, B., and Schöning, J. (2017). "The Geography of PokéMon GO: Beneficial and Problematic Effects on Places and Movement." In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Association for Computing Machinery. DOI: 10.1145/3025453.3025495.

[43] Conneller, C. (2011). "An Archaeology of Materials: Substantial Transformations in Early Prehistoric Europe." In: *Archaeological Journal* 168.1, pp. 406–406. DOI: 10.1080/00665983.2011.11020839.

[44] Dalsgaard, P. (2010). "Research in and through Design: An Interaction Design Research Approach." In: *Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction*. OZCHI '10. Association for Computing Machinery, pp. 200–203. DOI: 10.1145/1952222.1952265.

[45] Dalsgaard, P. and Halskov, K. (2010). "Designing Urban Media FaçAdes: Cases and Challenges." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Association for Computing Machinery, pp. 2277–2286. DOI: 10.1145/1753326.1753670.

[46] Dalsgaard, P., Halskov, K., and Wiethoff, A. (2016). "Designing Media Architecture: Tools and Approaches for Addressing the Main Design Challenges." In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. Association for Computing Machinery, pp. 2562–2573. DOI: 10.1145/2858036.2858318.

[47] Davies, N., Clinch, S., and Alt, F. (2014). "Pervasive displays: understanding the future of digital signage." In: *Synthesis Lectures on Mobile and Pervasive Computing* 8.1, pp. 1–128.

[48] Dijk, J. van (2013). "Creating traces, sharing insight: Explorations in embodied cognition design." PhD thesis. Eindhoven University of Technology. DOI: 10.6100/IR759609.

[49] Dong, T., Ackerman, M. S., and Newman, M. W. (2014). “"If These Walls Could Talk": Designing with Memories of Places.” In: *Proceedings of the 2014 Conference on Designing Interactive Systems*. DIS ’14. Association for Computing Machinery, pp. 63–72. DOI: 10.1145/2598510.2598605.

[50] Dourish, P. (2006). “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. Association for Computing Machinery, pp. 299–308. DOI: 10.1145/1180875.1180921.

[51] Du, R., Wills, K. R., Potasznik, M., and Froehlich, J. E. (2015). “AtmoSPHERE: Representing Space and Movement Using Sand Traces in an Interactive Zen Garden.” In: *Proceedings of the 33rd Annual ACM Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’15. Association for Computing Machinery, pp. 1627–1632. DOI: 10.1145/2702613.2732771.

[52] Fang, Y., Lin, W., Lau, C. T., and Lee, B.-S. (2011). “A visual attention model combining top-down and bottom-up mechanisms for salient object detection.” In: *2011 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. IEEE, pp. 1293–1296.

[53] Farnham, S. D., McCarthy, J. F., Patel, Y., Ahuja, S., Norman, D., Hazlewood, W. R., and Lind, J. (2009). “Measuring the Impact of Third Place Attachment on the Adoption of a Place-Based Community Technology.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’09. Association for Computing Machinery, pp. 2153–2156. DOI: 10.1145/1518701.1519028.

[54] Fauconnier, G. (2001). “Conceptual blending and analogy.” In: *The Analogical Mind: Perspectives from Cognitive Science*, pp. 255–285.

[55] Feijt, M. A., Westerink, J. H., Kort, Y. A. D., and IJsselsteijn, W. A. (2021). “Sharing biosignals: An analysis of the experiential and communication properties of interpersonal psychophysiology.” In: *Human–Computer Interaction* 0.0, pp. 1–30. DOI: 10.1080/07370024.2021.1913164.

[56] Fischer, P. and Hornecker, E. (2011). “Urban HCI – Interaction Patterns in the Built Environment.” In: DOI: 10.14236/ewic/HCI2011.2.

[57] Fisher, T. (2004). “What We Touch, Touches Us: Materials, Affects, and Affordances.” In: *Design Issues* 20, pp. 20–31. DOI: 10.1162/0747936042312066.

[58] Forkmann, T., Scherer, A., Meessen, J., Michal, M., Schächinger, H., Vögele, C., and Schulz, A. (2016). “Making sense of what you sense: Disentangling interoceptive awareness, sensibility and accuracy.” In: *International Journal of Psychophysiology* 109, pp. 71–80. DOI: https://doi.org/10.1016/j.ijpsycho.2016.09.019.

[59] Foth, M. and Caldwell, G. A. (2018). “More-than-Human Media Architecture.” In: *Proceedings of the 4th Media Architecture Biennale Conference*. MAB18. Association for Computing Machinery, pp. 66–75. DOI: 10.1145/3284389.3284495.

[60] Foulsham, T. and Kingstone, A. (2012). “Goal-Driven and Bottom-up Gaze in an Active Real-World Search Task.” In: *Proceedings of the Symposium on Eye Tracking Research*

and Applications. ETRA '12. Association for Computing Machinery, pp. 189–192. DOI: 10.1145/2168556.2168590.

[61] Frauenberger, C. (2019). "Entanglement HCI The Next Wave?" In: *ACM Trans. Comput.-Hum. Interact.* 27.1. DOI: 10.1145/3364998.

[62] Frey, J. (2016). "Remote Heart Rate Sensing and Projection to Renew Traditional Board Games and Foster Social Interactions." In: *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*. CHI EA '16. Association for Computing Machinery, pp. 1865–1871. DOI: 10.1145/2851581.2892391.

[63] Galinon-Mélénec, B. (2013). "From "Sign-Traces" to "Human-Trace": The Production and Interpretation of Traces from an Anthropological Perspective." In: *Intellectica* 59, pp. 89–113.

[64] Games, G. (2010(last accessed October 29th, 2021)). Horizon Zero Dawn. URL: https://horizon.fandom.com/wiki/Horizon_Zero_Dawn.

[65] Garfinkel, S. N., Seth, A. K., Barrett, A. B., Suzuki, K., and Critchley, H. D. (2015). "Knowing your own heart: Distinguishing interoceptive accuracy from interoceptive awareness." In: *Biological Psychology* 104, pp. 65–74. DOI: https://doi.org/10.1016/j.biopsycho.2014.11.004.

[66] Gaver, B. and Bowers, J. (2012). "Annotated Portfolios." In: *Interactions* 19.4, pp. 40–49. DOI: 10.1145/2212877.2212889.

[67] Gegenbauer, S. and Huang, E. M. (2012). "Inspiring the Design of Longer-Lived Electronics through an Understanding of Personal Attachment." In: *Proceedings of the Designing Interactive Systems Conference*. DIS '12. Association for Computing Machinery, pp. 635–644. DOI: 10.1145/2317956.2318052.

[68] Gelderblom, H. and Menge, L. (2018). "The Invisible Gorilla Revisited: Using Eye Tracking to Investigate Inattentional Blindness in Interface Design." In: *Proceedings of the 2018 International Conference on Advanced Visual Interfaces*. AVI '18. Association for Computing Machinery. DOI: 10.1145/3206505.3206550.

[69] Giaccardi, E. and Karana, E. (2015). "Foundations of Materials Experience: An Approach for HCI." In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Association for Computing Machinery, pp. 2447–2456. DOI: 10.1145/2702123.2702337.

[70] Giesel, M. and Zaidi, Q. (2011). "Visual perception of material affordances." In: *Journal of Vision* 11. DOI: 10.1167/11.11.356.

[71] Giesel, M. and Zaidi, Q. (2013). "Frequency-based heuristics for material perception." In: *Journal of Vision* 13. DOI: 10.1167/13.14.7.

[72] Gil, M., Giner, P., and Pelechano, V. (2012). "Personalization for Unobtrusive Service Interaction." In: *Personal Ubiquitous Comput.* 16.5, pp. 543–561. DOI: 10.1007/s00779-011-0414-0.

[73] Goffman, E. (2008). Behavior in Public Places. Free Press.

[74] Gokce, D. and Chen, F. (2020). "Multimodal and scale-sensitive assessment of sense of place in residential areas of Ankara, Turkey." In: *Journal of Housing and Built Environment*.

[75] Gračanin, D., Eltoweissy, M., Cheng, L., and Tasooji, R. (2018). "Reconfigurable Spaces and Places in Smart Built Environments: A Service Centric Approach." In: pp. 463–468. DOI: 10.1007/978-3-319-92285-0_63.

[76] Guan, J., Irizawa, J., and Morris, A. (2022). "Extended Reality and Internet of Things for Hyper-Connected Metaverse Environments." In: *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 163–168. DOI: 10.1109/VRW55335.2022.00043.

[77] Guimarães, M., Prada, R., Santos, P. A., Dias, J., Jhala, A., and Mascarenhas, S. (2020). "The Impact of Virtual Reality in the Social Presence of a Virtual Agent." In: *Proceedings of the 20th ACM International Conference on Intelligent Virtual Agents*. IVA '20. Association for Computing Machinery. DOI: 10.1145/3383652.3423879.

[78] Gustafson, P. (2001). "Meanings of Place: Everyday Experience And Theoretical Conceptualization." In: *Journal of Environmental Psychology* 21.1, pp. 5–16. DOI: https://doi.org/10.1006/jevp.2000.0185.

[79] Häkkilä, J., Colley, A., and Kalving, M. (2019). "Designing an Interactive Gravestone Display." In: *Proceedings of the 8th ACM International Symposium on Pervasive Displays*. PerDis '19. ACM, 4:1–4:7. DOI: 10.1145/3321335.3324952.

[80] Häkkilä, J., Forsman, M.-T., and Colley, A. (2018). "Navigating the Graveyard: Designing Technology for Deathscapes." In: pp. 199–204. DOI: 10.1145/3282894.3282912.

[81] Hansen, P. and Jespersen, A. (2013). "Nudge and the Manipulation of Choice: A Framework for the Responsible Use of the Nudge Approach to Behaviour Change in Public Policy." In: *European Journal of Risk Regulation* 1.

[82] Harrison, S. and Dourish, P. (1996). "Re-Place-Ing Space: The Roles of Place and Space in Collaborative Systems." In: *Proceedings of the 1996 ACM Conference on Computer Supported Cooperative Work*. CSCW '96. Association for Computing Machinery, pp. 67–76. DOI: 10.1145/240080.240193.

[83] Harun, N. Z., Mansor, M., and Said, I. (2015). "Place Rootedness Suggesting the Loss and Survival of Historical Public Spaces." In: *Procedia Environmental Sciences* 28. The 5th Sustainable Future for Human Security (SustaiN 2014), pp. 528–537. DOI: https://doi.org/10.1016/j.proenv.2015.07.063.

[84] Hassenzahl, M. and Tractinsky, N. (2006). "User experience - a research agenda." In: *Behaviour & Information Technology* 25.2, pp. 91–97. DOI: 10.1080/01449290500330331.

[85] Hello Games (2016 (last accessed October 29th, 2021)). No Man's Sky. URL: https://www.nomanssky.com/beyond-update/?cli_action=1635529112.09.

[86] Henderson, J. M. (2007). "Regarding Scenes." In: *Current Directions in Psychological Science* 16.4, pp. 219–222. DOI: 10.1111/j.1467-8721.2007.00507.x.

[87] Henderson, J. M., Hayes, T., Peacock, C. E., and Rehrig, G. (2019). "Meaning and Attentional Guidance in Scenes: A Review of the Meaning Map Approach." In: *Vision* 3 (2). DOI: 10.3390/vision3020019.

[88] Hespanhol, L. and Dalsgaard, P. (2015). "Social Interaction Design Patterns for Urban Media Architecture." In: *Human-Computer Interaction – INTERACT 2015*. Ed. by J. Abascal, S. Barbosa, M. Fetter, T. Gross, P. Palanque, and M. Winckler. Springer International Publishing, pp. 596–613.

[89] Hiiop, H. (2008). "The Possibility of Patina in Contemporary Art or, does the 'New Art' Have a Right to Get Old?" In: *Koht ja Paik. Place and Location. Studies in Environmental Aesthetics and Semiotics VI*. Ed. by E. Näripea, V. Sarapik, and J. Tomberg. Vol. 6, pp. 153–166.

[90] Hirsch, L., Welsch, R., Rossmy, B., and Butz, A. (2022f). "Embedded AR Storytelling Supports Active Indexing at Historical Places." In: *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '22. Association for Computing Machinery. DOI: 10.1145/3490149.3501328.

[91] Hoggenmueller, M., Hespanhol, L., and Tomitsch, M. (2020a). "Stop and Smell the Chalk Flowers: A Robotic Probe for Investigating Urban Interaction with Physicalised Displays." In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI '20. Association for Computing Machinery, pp. 1–14. DOI: 10.1145/3313831.3376676.

[92] Hoggenmueller, M., Tomitsch, M., and Fredericks, J. (2020b). "Bringing Sustainability-Sensitivity into the Design of Public Interfaces: Opportunities and Challenges." Position paper presented at the SelfSustainableCHI workshop in conjunction with CHI Conference on Human Factors in Computing Systems.

[93] Höök, K. and Löwgren, J. (2012). "Strong Concepts: Intermediate-Level Knowledge in Interaction Design Research." In: *ACM Trans. Comput.-Hum. Interact.* 19.3. DOI: 10.1145/2362364.2362371.

[94] Hornecker, E. (2016). "The To-and-Fro of Sense Making: Supporting Users' Active Indexing in Museums." In: *ACM Trans. Comput.-Hum. Interact.* 23.2. DOI: 10.1145/2882785.

[95] Hornecker, E., Honauer, M., and Ciolfi, L. (2014). "Exploring historical cemeteries as a site for technological augmentation." In: *iHCI 2014: Proceedings of the 8th Irish Human Computer Interaction Conference*. Ed. by R. Albatal, J. Doyle, Y. Yang, A. Smeaton, and N. Caprani. Proceeding of the conference: iHCI 2014, Irish Human-Computer Interaction Conference : ?Shaping our digital lives?, held at Dublin, Ireland, on 1-2 September 2014. Organised by Dublin City University. Dublin City University, pp. 93–96.

[96] Hornecker, E. and Stifter, M. (2006). "Learning from Interactive Museum Installations about Interaction Design for Public Settings." In: *Proceedings of the 18th Australia Conference on Computer-Human Interaction: Design: Activities, Artefacts and Environments*. OZCHI '06. Association for Computing Machinery, pp. 135–142. DOI: 10.1145/1228175.1228201.

[97] Houben, M., Denef, B., Mattelaer, M., Claes, S., and Vande Moere, A. (2017). "The Meaningful Integration of Interactive Media in Architecture." In: *Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems*. DIS '17 Companion. Association for Computing Machinery, pp. 187–191. DOI: 10.1145/3064857.3079143.

[98] Hoven, E. van den (2014). "A future-proof past: Designing for remembering experiences." In: *Memory Studies* 7, pp. 370–384. DOI: 10.1177/1750698014530625.

[99] Howell, N., Niemeyer, G., and Ryokai, K. (2019). "Life-Affirming Biosensing in Public: Sounding Heartbeats on a Red Bench." In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Association for Computing Machinery, pp. 1–16. DOI: 10.1145/3290605.3300910.

[100] Hsieh, C.-K., Yang, L., Wei, H., Naaman, M., and Estrin, D. (2016). "Immersive Recommendation: News and Event Recommendations Using Personal Digital Traces." In: *Proceedings of the 25th International Conference on World Wide Web*. WWW '16. International World Wide Web Conferences Steering Committee, pp. 51–62. DOI: 10.1145/2872427.2883006.

[101] Huang, S., Ranganathan, S. P. B., and Parsons, I. (2020). "To Touch or Not to Touch? Comparing Touch, Mid-Air Gesture, Mid-Air Haptics for Public Display in Post COVID-19 Society." In: *SIGGRAPH Asia 2020 Posters*. SA '20. Association for Computing Machinery. DOI: 10.1145/3415264.3425438.

[102] Hummels, C. and Dijk, J. van (2015). "Seven Principles to Design for Embodied Sensemaking." In: *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '15. Association for Computing Machinery, pp. 21–28. DOI: 10.1145/2677199.2680577.

[103] Ingold, T. (2013). Making Anthropology, Archaeology, Art and Architecture. DOI: 10.4324/9780203559055.

[104] Innocent, T. and Haines, S. (2007). "Nonverbal Communication in Multiplayer Game Worlds." In: *Proceedings of the 4th Australasian Conference on Interactive Entertainment*. IE '07. RMIT University.

[105] Jetter, H.-C., Schröder, J.-H., Gugenheimer, J., Billinghurst, M., Anthes, C., Khamis, M., and Feuchtner, T. (2021). "Transitional Interfaces in Mixed and Cross-Reality: A New Frontier?" In: *Companion Proceedings of the 2021 Conference on Interactive Surfaces and Spaces*. ISS '21. Association for Computing Machinery, pp. 46–49. DOI: 10.1145/3447932.3487940.

[106] Jonas, M., Said, S., Yu, D., Aiello, C., Furlo, N., and Zytko, D. (2019). "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. Association for Computing Machinery, pp. 437–444. DOI: 10.1145/3341215.3356271.

[107] Jones, S. (2016). "Wrestling with the Social Value of Heritage: Problems, Dilemmas and Opportunities." In: *Journal of Community Archaeology & Heritage* 4, pp. 1–17. DOI: 10.1080/20518196.2016.1193996.

[108] Judson, E. and Iyer-Raniga, U. (2010). “Reinterpreting the value of built heritage for sustainable development.” In: *Heritage 2010: Heritage and Sustainable development*. Vol. 24. 2.

[109] Karana, E., Barati, B., Rognoli, V., and Zeeuw van der Laan, A. (2015). “Material Driven Design (MDD): A Method to Design for Material Experiences.” In: *International Journal of Design* in press.

[110] Karana, E., Pedgley, O., Rognoli, V., and authors (2013). Materials Experience: Fundamentals of Materials and Design. Elsevier.

[111] Karimi, R., Farahzadi, L., Sepasgozar, S., Sargolzaei, S., Sepasgozar, S., Zareian, M., and Nasrolahi, A. (2021). “Smart Built Environment Including Smart Home, Smart Building and Smart City: Definitions and Applied Technologies.” In: DOI: 10.5772/intechopen.95104.

[112] Kaur, J., Devgon, R., Goel, S., Singh, A., Monteiro, K., and Singh, A. (2023). “Future of Intimate Artefacts: A Speculative Design Investigation.” In: *Proceedings of the 13th Indian Conference on Human-Computer Interaction*. IndiaHCI ’22. Association for Computing Machinery, pp. 57–66. DOI: 10.1145/3570211.3570216.

[113] Kim, D., Han, K., Sim, J. S., and Noh, Y. (2018). “Smombie Guardian: We watch for potential obstacles while you are walking and conducting smartphone activities.” In: *PLOS ONE* 13.6, pp. 1–21. DOI: 10.1371/journal.pone.0197050.

[114] Kim, H. and Lee, W. (2009). “Designing Unobtrusive Interfaces with Minimal Presence.” In: *CHI ’09 Extended Abstracts on Human Factors in Computing Systems*. CHI EA ’09. Association for Computing Machinery, pp. 3673–3678. DOI: 10.1145/1520340.1520553.

[115] Kim, J. and Maher, M. L. (2019). “Metaphors, Signifiers, Affordances, and Modalities for Designing Mobile and Embodied Interactive Systems.” In: *Proceedings of the 31st Australian Conference on Human-Computer-Interaction*. OZCHI’19. Association for Computing Machinery, pp. 542–545. DOI: 10.1145/3369457.3369527.

[116] Kirsh, D. (2019). “Do Architects and Designers Think about Interactivity Differently?” In: *ACM Trans. Comput.-Hum. Interact.* 26.2. DOI: 10.1145/3301425.

[117] Kiss, F. and Schmidt, A. (2019). “Stressed by Design? The Problems of Transferring Interaction Design from Workstations to Mobile Interfaces.” In: *Proceedings of the 13th EAI International Conference on Pervasive Computing Technologies for Healthcare*. PervasiveHealth’19. Association for Computing Machinery, pp. 377–382. DOI: 10.1145/3329189.3329232.

[118] Kojima Productions (2019 (last accessed October 29th, 2021)). Death Stranding.

[119] Kostopoulou, E., Javornik, A., Koutsolampros, P., Julier, S., and Fatah gen. Schieck, A. (2018). “Mediated Spatial Narratives: Experiencing Archival Material and Shared Memories in Urban Space.” In: *Proceedings of the 4th Media Architecture Biennale Conference*. MAB18. Association for Computing Machinery, pp. 118–127. DOI: 10.1145/3284389.3284395.

[120] Kravi, E. (2016). "Understanding User Behavior From Online Traces." In: *Proceedings of the 2016 on SIGMOD'16 PhD Symposium*. SIGMOD'16 PhD. Association for Computing Machinery, pp. 27–31. DOI: 10.1145/2926693.2929901.

[121] Krösche, J., Baldzer, J., and Boll, S. (2004). "MobiDENK-Mobile Multimedia in Monument Conservation." In: *IEEE MultiMedia* 11.2, pp. 72–77. DOI: 10.1109/MMUL.2004.1289043.

[122] Kučera, J., Scott, J., and Chen, N. (2017). "Probing Calmness in Applications Using a Calm Display Prototype." In: *Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers*. UbiComp '17. ACM, pp. 965–969. DOI: 10.1145/3123024.3124564.

[123] Kuipers, M. and Jong, W. de (2017). Designing from Heritage - Strategies for Conservation and Conversion. NY: Basic Books, p. 33.

[124] Kujala, S. and Kauppinen, M. (2004). "Identifying and Selecting Users for User-Centered Design." In: *Proceedings of the Third Nordic Conference on Human-Computer Interaction*. NordiCHI '04. Association for Computing Machinery, pp. 297–303. DOI: 10.1145/1028014.1028060.

[125] Kumar, D., Maharjan, R., Maxhuni, A., Dominguez, H., Frølich, A., and Bardram, J. E. (2022). "MCardia: A Context-Aware ECG Collection System for Ambulatory Arrhythmia Screening." In: *ACM Trans. Comput. Healthcare* 3.2. DOI: 10.1145/3494581.

[126] Kwok, T. C., Kiefer, P., and Raubal, M. (2023). "Unobtrusive interaction: a systematic literature review and expert survey." In: *Human–Computer Interaction* 0.0, pp. 1–37. DOI: 10.1080/07370024.2022.2162404.

[127] Lange, M. and Waal, M. de (2017). "Chapter 4 Owning the City: New Media and Citizen Engagement in Urban Design: Community-Based Planning." In: pp. 87–110. DOI: 10.1201/9781315365794-5.

[128] Latour, B. (2005). Reassembling the Social – An Introduction to Actor-Network-Theory. 1st. Oxford University Press.

[129] Lavigne, G., Vallerand, R., and Crevier-Braud, L. (2011). "The Fundamental Need to Belong." In: *Personality & social psychology bulletin* 37, pp. 1185–201. DOI: 10.1177/0146167211405995.

[130] Lee, M.-H., Son, O., and Nam, T.-J. (2016). "Patina-Inspired Personalization: Personalizing Products with Traces of Daily Use." In: *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. DIS '16. Association for Computing Machinery, pp. 251–263. DOI: 10.1145/2901790.2901812.

[131] Lee, S., Ahn, H., Han, J., and Lee, Y.-B. (2013). "Visual Attention with Contextual Saliencies of a Scene." In: *Proceedings of the 7th International Conference on Ubiquitous Information Management and Communication*. ICUIMC '13. Association for Computing Machinery. DOI: 10.1145/2448556.2448647.

[132] Leifer, L. (2008). “The Design of Implicit Interactions: Making Interactive Systems Less Obnoxious.” In: *Design Issues* 24, pp. 72–84. DOI: `10.1162/desi.2008.24.3.72`.

[133] Lentini, L. and Decortis, F. (2010). “Space and places: When interacting with and in physical space becomes a meaningful experience.” In: *Personal and Ubiquitous Computing* 14, pp. 407–415. DOI: `10.1007/s00779-009-0267-y`.

[134] Li, B., Chen, B., Wu, Y., Wang, J., Yan, X., and Yang, Y. (2020). “Identifying the Motives of Using Weibo from Digital Traces.” In: *Proceedings of the 4th International Conference on Natural Language Processing and Information Retrieval*. NLPIR 2020. Association for Computing Machinery, pp. 169–172. DOI: `10.1145/3443279.3443294`.

[135] Li, J., Hirsch, L., Lu, T., Mayer, S., and Butz, A. (2022). “A Touch of Realities: Car-Interior-Based Haptic Interaction Supports In-Car VR Recovery from Interruptions.” In: *Proceedings of Mensch Und Computer 2022*. MuC ’22. Association for Computing Machinery, pp. 229–239. DOI: `10.1145/3543758.3543768`.

[136] Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., and Moher, D. (2009). “The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration.” In: *BMJ* 339. DOI: `10.1136/bmj.b2700`. eprint: `https://www.bmj.com/content/339/bmj.b2700.full.pdf`.

[137] Lindroth, T. and Bergquist, M. (2008). “Breadcrumbs of Interaction: Situating Personal Information Management.” In: *Proceedings of the 5th Nordic Conference on Human-Computer Interaction: Building Bridges*. NordiCHI ’08. Association for Computing Machinery, pp. 266–273. DOI: `10.1145/1463160.1463189`.

[138] Liu, H. and Li, B. (2021). “Changes of Spatial Characteristics: Socio-Cultural Sustainability in Historical Neighborhood in Beijing, China.” In: *Sustainability* 13.11. DOI: `10.3390/su13116212`.

[139] Lundgaard, S. S., Kjeldskov, J., and Skov, M. B. (2019). “Temporal Constraints in Human–Building Interaction.” In: *ACM Trans. Comput.-Hum. Interact.* 26.2. DOI: `10.1145/3301424`.

[140] Mack, A. and Rock, I. (1998). “Inattentional blindness: Perception without attention.” In: *Visual attention* 8, pp. 55–76.

[141] Mäkelä, V., Winter, J., Schwab, J., Koch, M., and Alt, F. (2022). “Pandemic Displays: Considering Hygiene on Public Touchscreens in the Post-Pandemic Era.” In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI ’22. Association for Computing Machinery. DOI: `10.1145/3491102.3501937`.

[142] Malinverni, L., Maya, J., Schaper, M.-M., and Pares, N. (2017). “The World-as-Support: Embodied Exploration, Understanding and Meaning-Making of the Augmented World.” In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Association for Computing Machinery, pp. 5132–5144. DOI: `10.1145/3025453.3025955`.

[143] Manzo, L. C. (2005). “For better or worse: Exploring multiple dimensions of place meaning.” In: *Journal of Environmental Psychology* 25, pp. 67–86.

[144] Markman, A. and Gentner, D. (2000). “Structure Mapping in the Comparison Process.” In: *The American Journal of Psychology* 113.4, pp. 501–538. DOI: 10.2307/1423470.

[145] Maslow, A. H. (2013). “A Theory of Human Motivation.” In: Wilder Publications.

[146] Mason, J. (2014). “‘Does it Make Sense’ or ‘What Does it Mean’?” In: *Proceedings of the 22nd International Conference on Computers in Education, ICCE 2014*. Vol. 1.

[147] McVeigh-Schultz, J., Kolesnichenko, A., and Isbister, K. (2019). “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.

[148] Mekler, E. D. and Hornbæk, K. (2019). “A Framework for the Experience of Meaning in Human-Computer Interaction.” In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI ’19. Association for Computing Machinery, pp. 1–15. DOI: 10.1145/3290605.3300455.

[149] Milgram, P. and Kishino, F. (1994). “A Taxonomy of Mixed Reality Visual Displays.” In: *IEICE Trans. Information Systems* vol. E77-D, no. 12, pp. 1321–1329.

[150] Mols, I., Hoven, E. v. d., and Eggen, B. (2014). “Making Memories: A Cultural Probe Study into the Remembering of Everyday Life.” In: *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*. NordiCHI ’14. Association for Computing Machinery, pp. 256–265. DOI: 10.1145/2639189.2639209.

[151] Monastero, B. and McGookin, D. K. (2018). “Traces: Studying a Public Reactive Floor-Projection of Walking Trajectories to Support Social Awareness.” In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, pp. 1–13. DOI: 10.1145/3173574.3174061.

[152] Moore, G., Croxford, B., Adams, M., Refaee, M., Cox, T., and Sharples, S. (2008). “The photo-survey research method: capturing life in the city.” In: *Visual Studies* 23, pp. 50–62. DOI: 10.1080/14725860801908536.

[153] Neumann, O. (1987). “Beyond Capacity: A Functional View of Attention.” In: *Perspectives on Perception and Action*. Ed. by H. Heuer and A. F. Sanders. Erlbaum.

[154] Nguyen, Q., Himmelsbach, J., Bertel, D., Zechner, O., and Tscheligi, M. (2022). “What Is Meaningful Human-Computer Interaction? Understanding Freedom, Responsibility, and Noos in HCI Based on Viktor Frankl’s Existential Philosophy.” In: *Designing Interactive Systems Conference*. DIS ’22. Association for Computing Machinery, pp. 654–665. DOI: 10.1145/3532106.3533484.

[155] Nisi, V., Costanza, E., and Dionisio, M. (2016). “Placing Location-Based Narratives in Context Through a Narrator and Visual Markers.” In: *Interacting with Computers* 29.3. DOI: 10.1093/iwc/iww020.

[156] Nofal, E., Reffat, M., Vande Moere, A., Beck, D., Allison, C., Morgado, L., Pirker, J., Khosmood, F., Richter, J., and Gütl, C. (2017). Phygital Heritage: an Approach for Heritage Communication. DOI: 10.3217/978-3-85125-530-0-36.

[157] Norman, D. A. (2008). “THE WAY I SEE IT Signifiers, Not Affordances.” In: *Interactions* 15.6, pp. 18–19. DOI: 10.1145/1409040.1409044.

[158] Norman, D. A. (1988). The psychology of everday things. NY: Basic Books, pp. 114–120.

[159] Norman, D. A. (2010). “Natural User Interfaces Are Not Natural.” In: *Interactions* 17.3, pp. 6–10. DOI: 10.1145/1744161.1744163.

[160] Norsidah Ujang, M. K. and Maulan, S. (2018). “Linking place attachment and social interaction: towards meaningful public places.” In: *Journal of Place Management and Development* 11.1, pp. 115–129. DOI: 10.1108/JPMD-01-2017-0012.

[161] Oduor, M. and Perälä, T. (2021). “Interactive Urban Play to Encourage Active Mobility: Usability Study of a Web-Based Augmented Reality Application.” In: *Frontiers in Computer Science* 3. DOI: 10.3389/fcomp.2021.706162.

[162] Offenhuber, D. and Seitinger, S. (2014). “Over the Rainbow: Information Design for Low-Resolution Urban Displays.” In: *Proceedings of the 2nd Media Architecture Biennale Conference: World Cities*. MAB ’14. Association for Computing Machinery, pp. 40–47. DOI: 10.1145/2682884.2682886.

[163] Olwal, A. and Dementyev, A. (2022). “Hidden Interfaces for Ambient Computing: Enabling Interaction in Everyday Materials through High-Brightness Visuals on Low-Cost Matrix Displays.” In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI ’22. Association for Computing Machinery. DOI: 10.1145/3491102.3517674.

[164] Ouzts, A. D., Duchowski, A. T., Gomes, T., and Hurley, R. A. (2012). “On the conspicuity of 3-D fiducial markers in 2-D projected environments.” In: *Proceedings of the Symposium on Eye Tracking Research and Applications*, pp. 325–328. DOI: https://doi.org/10.1145/2168556.2168627.

[165] Parker, C., Caldwell, G. A., and Fredericks, J. (2019). “The Impact of Hyperconnectedness on Urban HCI: Challenges and Opportunities.” In: *Proceedings of the 31st Australian Conference on Human-Computer-Interaction*. OZCHI’19. Association for Computing Machinery, pp. 480–484. DOI: 10.1145/3369457.3369521.

[166] Parker, C., Tomitsch, M., Davies, N., Valkanova, N., and Kay, J. (2020). “Foundations for Designing Public Interactive Displays That Provide Value to Users.” In: *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. CHI ’20. Association for Computing Machinery, pp. 1–12. DOI: 10.1145/3313831.3376532.

[167] Petrelli, D., Ciolfi, L., Dijk, D. van, Hornecker, E., Not, E., and Schmidt, A. (2013). “Integrating Material and Digital: A New Way for Cultural Heritage.” In: *Interactions* 20.4, pp. 58–63. DOI: 10.1145/2486227.2486239.

[168] Pichlmair, M. and Johansen, M. (2020). “Designing Game Feel. A Survey.” In: *CoRR* abs/2011.09201. arXiv: 2011.09201.

[169] Plutchik, R. (2003). “Emotions & Life: Perspectives from Psychology, Biology and Evolution.” In: American Psychological Association.

[170] Poggel, D., Strasburger, H., and Mackeben, M. (2007). “Cueing Attention by Relative Motion in the Periphery of the Visual Field.” In: *Perception* 36, pp. 955–70. DOI: 10.1068/p5752.

[171] Proulx, T. and Inzlicht, M. (2012). “The Five “A”s of Meaning Maintenance: Finding Meaning in the Theories of Sense-Making.” In: *Psychological Inquiry* 23.4, pp. 317–335. DOI: 10.1080/1047840X.2012.702372.

[172] Ramic-Brkic, B., Chalmers, A., Sadzak, A., Debattista, K., and Sultanic, S. (2013). “Exploring multiple modalities for selective rendering of virtual environments.” In: *Proceedings of the 29th Spring Conference on Computer Graphics*, pp. 91–98. DOI: https://doi.org/10.1145/2508244.2508256.

[173] Raymond, C. M., Kyttä, M., and Stedman, R. (2017). “Sense of Place, Fast and Slow: The Potential Contributions of Affordance Theory to Sense of Place.” In: *Frontiers in Psychology* 8, p. 1674. DOI: 10.3389/fpsyg.2017.01674.

[174] Rensink, R., O’Regan, J., and Clark, J. (1997). “To See or not to See: The Need for Attention to Perceive Changes in Scenes.” In: *Psychological Science* 8, pp. 368–373. DOI: 10.1111/j.1467-9280.1997.tb00427.x.

[175] Renswouw, L. van, Hamersveld, Y. van, Huibers, H., Vos, S., and Lallemand, C. (2022). “Fontana: Triggering Physical Activity and Social Connectedness through an Interactive Water Installation.” In: *Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI EA ’22. Association for Computing Machinery. DOI: 10.1145/3491101.3519765.

[176] Rice, J., Kozak, R., Meitner, M., and Cohen, D. (2007). “Appearance wood products and psychological well-being.” In: *Wood and Fiber Science* 38.

[177] Riekki, J., Isomursu, P., and Isomursu, M. (2004). “Evaluating the Calmness of Ubiquitous Applications.” In: *Product Focused Software Process Improvement*. Ed. by F. Bomarius and H. Iida. Springer Berlin Heidelberg, pp. 105–119.

[178] Robbins, H., Giaccardi, E., and Karana, E. (2016). “Traces as an Approach to Design for Focal Things and Practices.” In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. NordiCHI ’16. Association for Computing Machinery. DOI: 10.1145/2971485.2971538.

[179] Rognoli, V., Ferraro, V., and Parisi, S. (2021). “ICS Materiality: the phenomenon of interactive, connected, and smart materials as enablers of new materials experiences.” In: FrancoAngeli.

[180] Rogowitz, B., Perovich, L., Li, Y., Kierulf, B., and Offenhuber, D. (2021). “Touching Art – A Method for Visualizing Tactile Experience.” In: *This manuscript was presented at alt.VIS, a workshop co-located with IEEE VIS 2021 (held virtually)*.

[181] Rollero, C. and Piccoli, N. (2010). “Does place attachment affect social well-being?” In: *European Review of Applied Psychology-revue Europeenne De Psychologie Appliquee - EUR REV APPL PSYCHOL* 60, pp. 233–238. DOI: 10.1016/j.erap.2010.05.001.

[182] Rosner, D. K., Ikemiya, M., Kim, D., and Koch, K. (2013). "Designing with traces." In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM Press, pp. 1649–1658. DOI: 10.1145/2470654.2466218.

[183] Roßmy, B. (2021). "Designing speculative artifacts." DOI: 10.5282/edoc.29413.

[184] Scannell, L. and Gifford, R. (2014). "The psychology of place attachment." In: ed. by R. Clifford. Optimal Books.

[185] Schmidt, A. (1999). "Implicit Human Computer Interaction Through Context." In: *Personal Technologies* 4. DOI: 10.1007/BF01324126.

[186] Schoffelen, J., Claes, S., Huybrechts, L., Martens, S., Chua, A., and Moere, A. V. (2015). "Visualising things. Perspectives on how to make things public through visualisation." In: *CoDesign* 11.3-4, pp. 179–192. DOI: 10.1080/15710882.2015.1081240.

[187] Semsioglu, S., Karaturhan, P., Akbas, S., and Yantac, A. E. (2021). "Isles of Emotion: Emotionally Expressive Social Virtual Spaces for Reflection and Communication." In: *Creativity and Cognition*. C&C '21. Association for Computing Machinery. DOI: 10.1145/3450741.3466805.

[188] Sepe, M. (2012). "Principles for place identity enhancement: a sustainable challenge for changes to the contemporary city." In: *WIT Transactions on Ecology and the Environment* 155, pp. 993–1004.

[189] Shirvani Dastgerdi, A. and De Luca, G. (2019). "Specifying the Significance of Historic Sites in Heritage Planning." In: *Conservation Science in Cultural Heritage* 18, pp. 29–39. DOI: 10.6092/issn.1973-9494/9225.

[190] Shneiderman, B. and Rose, A. (1996). "Social Impact Statements: Engaging Public Participation in Information Technology Design." In: *Proceedings of the Symposium on Computers and the Quality of Life*. CQL '96. Association for Computing Machinery, pp. 90–96. DOI: 10.1145/238339.238378.

[191] Sifonis, C. M. (2017). "Attributes of Ingress Gaming Locations Contributing to Players' Place Attachment." In: *Extended Abstracts Publication of the Annual Symposium on Computer-Human Interaction in Play*. CHI PLAY '17 Extended Abstracts. Association for Computing Machinery, pp. 569–575. DOI: 10.1145/3130859.3131338.

[192] Simons, D. and Chabris, C. (1999). "Gorillas in Our Midst: Sustained Inattentional Blindness for Dynamic Events." In: *Perception* 28, pp. 1059–74. DOI: 10.1068/p2952.

[193] Skarbez, R., Smith, M., and Whitton, M. C. (2021). "Revisiting Milgram and Kishino's Reality-Virtuality Continuum." In: *Frontiers in Virtual Reality* 2. DOI: 10.3389/frvir.2021.647997.

[194] Speicher, M., Hall, B. D., and Nebeling, M. (2019). "What is Mixed Reality?" In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. Association for Computing Machinery, pp. 1–15. DOI: 10.1145/3290605.3300767.

[195] Stals, S., Smyth, M., and Ijsselsteijn, W. (2014). "Walking & Talking: Probing the Urban Lived Experience." In: *Proceedings of the 8th Nordic Conference on Human-Computer In-*

teraction: Fun, Fast, Foundational. NordiCHI '14. Association for Computing Machinery, pp. 737–746. DOI: 10.1145/2639189.2641215.

[196] Stals, S., Smyth, M., and Mival, O. (2017). "Exploring People's Emotional Bond with Places in the City: A Pilot Study." In: *Proceedings of the 2017 ACM Conference Companion Publication on Designing Interactive Systems*. DIS '17 Companion. Association for Computing Machinery, pp. 207–212. DOI: 10.1145/3064857.3079147.

[197] Stenros, J., Paavilainen, J., and Mäyrä, F. (2009). "The Many Faces of Sociability and Social Play in Games." In: *Proceedings of the 13th International MindTrek Conference: Everyday Life in the Ubiquitous Era*. MindTrek '09. Association for Computing Machinery, pp. 82–89. DOI: 10.1145/1621841.1621857.

[198] Stepanova, E. R., Desnoyers-Stewart, J., Höök, K., and Riecke, B. E. (2022). "Strategies for Fostering a Genuine Feeling of Connection in Technologically Mediated Systems." In: *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems*. CHI '22. Association for Computing Machinery. DOI: 10.1145/3491102.3517580.

[199] Stephanidis, C. C., Salvendy, G., Group Margherita Antona, M. of the, Chen, J. Y. C., Dong, J., Duffy, V. G., Fang, X., Fidopiastis, C., Fragomeni, G., Fu, L. P., Guo, Y., Harris, D., Ioannou, A., Jeong, K.-a. (, Konomi, S., Krömker, H., Kurosu, M., Lewis, J. R., Marcus, A., Meiselwitz, G., Moallem, A., Mori, H., Nah, F. F.-H., Ntoa, S., Rau, P.-L. P., Schmorrow, D., Siau, K., Streitz, N., Wang, W., Yamamoto, S., Zaphiris, P., and Zhou, J. (2019). "Seven HCI Grand Challenges." In: *International Journal of Human–Computer Interaction* 35.14, pp. 1229–1269. DOI: 10.1080/10447318.2019.1619259.

[200] Streitz, N. A. (2007). "From Human–Computer Interaction to Human–Environment Interaction: Ambient Intelligence and the Disappearing Computer." In: *Universal Access in Ambient Intelligence Environments*. Ed. by C. Stephanidis and M. Pieper. Springer Berlin Heidelberg, pp. 3–13.

[201] Torsi, S., Ardito, C., and Rebek, C. (2020). "An Interactive Narrative to Improve Cultural Heritage Experience in Elementary School Children." In: *J. Comput. Cult. Herit.* 13.3. DOI: 10.1145/3382771.

[202] Tsai, W.-C. and Hoven, E. van den (2018). "Memory Probes: Exploring Retrospective User Experience Through Traces of Use on Cherished Objects." In: *International Journal of Design* 12.3, pp. 57–72.

[203] Van Waart, P. and Mulder, I. (2014). "Meaningful Interactions in a Smart City." In: DOI: 10.1007/978-3-319-07788-8_57.

[204] Vande Moere, A. and Hill, D. (2012). "Designing for the Situated and Public Visualization of Urban Data." In: *Journal of Urban Technology*. DOI: 10.1080/10630732.2012.698065.

[205] Vande Moere, A. and Wouters, N. (2012). "The Role of Context in Media Architecture." In: *Proceedings of the 2012 International Symposium on Pervasive Displays*. PerDis '12. Association for Computing Machinery. DOI: 10.1145/2307798.2307810.

[206] Verghese, P. and Pelli, D. (1992). "The information capacity of visual attention." In: *Vision Research* 32, pp. 983–995.

[207] Wang, M., Boring, S., and Greenberg, S. (2012). "Proxemic Peddler: A Public Advertising Display That Captures and Preserves the Attention of a Passerby." In: *Proceedings of the 2012 International Symposium on Pervasive Displays*. PerDis '12. Association for Computing Machinery. DOI: 10.1145/2307798.2307801.

[208] Wang, Y. and Green, K. E. (2019). "A Pattern-Based, Design Framework for Designing Collaborative Environments." In: *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '19. Association for Computing Machinery, pp. 595–604. DOI: 10.1145/3294109.3295652.

[209] Ware, C. (2019). Information visualization: perception for design. Morgan Kaufmann.

[210] Webb, E., Campbell, D., Schwartz, R., and Sechrest, L. (2000). Unobtrusive Measures. Sage classics. SAGE Publications.

[211] Wei, H., Hsieh, C.-K., Yang, L., and Estrin, D. (2016). "GroupLink: Group Event Recommendations Using Personal Digital Traces." In: *Proceedings of the 19th ACM Conference on Computer Supported Cooperative Work and Social Computing Companion*. CSCW '16 Companion. Association for Computing Machinery, pp. 110–113. DOI: 10.1145/2818052.2874338.

[212] Weiser, M. (1999). "The Computer for the 21st Century." In: *SIGMOBILE Mob. Comput. Commun. Rev.* 3.3, pp. 3–11. DOI: 10.1145/329124.329126.

[213] Weiser, M. and Brown, J. S. (1997). "The Coming Age of Calm Technolgy." In: *Beyond Calculation: The next Fifty Years*. Copernicus, pp. 75–85.

[214] Welankar, N. (2020). "How Can Designers Fight the Coronavirus?" In: *Interactions* 27.4, pp. 56–58. DOI: 10.1145/3404209.

[215] Wiberg, M. (2018). The Materiality of Interaction. MIT Press.

[216] Wiberg, M. (2014). "Methodology for materiality: interaction design research through a material lens." In: *Personal and Ubiquitous Computing* 18, pp. 625–636. DOI: 10.1007/s00779-013-0686-7.

[217] Wiberg, M. and Stolterman, E. (2008). "Environment Interaction: Character, Challenges & Implications for Design." In: *Proceedings of the 7th International Conference on Mobile and Ubiquitous Multimedia*. MUM '08. Association for Computing Machinery, pp. 15–22. DOI: 10.1145/1543137.1543141.

[218] Wiethoff, A. and Hussmann, H. (2017). Media Architecture: Using Information and Media as Construction Material. Walter de Gruyter GmbH, p. 1.

[219] Wouters, N. (2016). "Contextualising Media Architecture: Design Approaches to Support Social and Architectural Relevance." PhD thesis. DOI: 10.13140/RG.2.2.11496.67840.

[220] Wouters, N., Downs, J., Harrop, M., Cox, T., Oliveira, E., Webber, S., Vetere, F., and Vande Moere, A. (2016). "Uncovering the Honeypot Effect: How Audiences Engage with Public Interactive Systems." In: *Proceedings of the 2016 ACM Conference on Designing*

Interactive Systems. DIS ’16. Association for Computing Machinery, pp. 5–16. DOI: 10.1145/2901790.2901796.

[221] Wouters, N., Huyghe, J., and Moere, A. V. (2014). “StreetTalk: Participative Design of Situated Public Displays for Urban Neighborhood Interaction.” In: *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*. NordiCHI ’14. Association for Computing Machinery, pp. 747–756. DOI: 10.1145/2639189.2641211.

[222] Zhang, P. and Soergel, D. (2014). “Towards a comprehensive model of the cognitive process and mechanisms of individual sensemaking.” In: *Journal of the Association for Information Science and Technology* 65.9, pp. 1733–1756. DOI: https://doi.org/10.1002/asi.23125.

[223] Zimmerman, J., Forlizzi, J., and Evenson, S. (2007). “Research through Design as a Method for Interaction Design Research in HCI.” In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’07. Association for Computing Machinery, pp. 493–502. DOI: 10.1145/1240624.1240704.

Contextualizing Urban Interfaces through *Traces in Use* for Meaningful Interactions

LINDA HIRSCH, LMU Munich, Germany
MARIUS HOGGENMUELLER, University of Sydney, Australia
CEENU GEORGE, University of Augsburg, Germany
LOUISA BEKKER, SARITA SRIDHARAN, and ANDREAS BUTZ, LMU Munich, Germany

Designing meaningful interactions with and in shared places can positively influence users' long-term well-being. However, creating such interactions is a continuous, complex challenge due to a lack of design concepts and tools transferable across contexts. Based on literature and expert interviews, we define a *Traces in Use* design concept to contextualize interfaces for meaningful interactions in urban environments (N=8). Applying a research in and through design approach, we explore the concept by developing, contextualizing, and testing three interfaces in two empirical field studies (N=40), a lion interface, a drum, and a storyteller. The results confirm that the concept promotes meaningful interaction by supporting users' feelings of socio-cultural connectedness and sense-making. With this, our work contributes the *Traces in Use* design concept and its methodological application for meaningful interactions in urban places.

CCS Concepts: • **Human-centered computing → Empirical studies in interaction design**; **Interaction design theory, concepts and paradigms**; **Empirical studies in ubiquitous and mobile computing**.

Additional Key Words and Phrases: contextualized interfaces, meaning of place, traces of use, embedded interfaces, materials experience

ACM Reference Format:
Linda Hirsch, Marius Hoggenmueller, Ceenu George, Louisa Bekker, Sarita Sridharan, and Andreas Butz. 2022. Contextualizing Urban Interfaces through *Traces in Use* for Meaningful Interactions. *ACM Trans. Comput.-Hum. Interact.* 37, 4, Article 111 (December 2022), 41 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

"*[...] Towns and buildings will not be able to become alive, unless they are made by all the people in society, and unless these people share a common pattern language within which to make these buildings, and unless this common pattern language is alive itself*" –Alexander et al. [2]. Two of the main challenges in urban interaction design (Urban IxD) are the contextualization of public interfaces [17] and catering to the needs and interests of a heterogeneous group of people [46, 103]. Contextualized interfaces are embedded into the built environment, representing the local identity, promoting engagement, and fostering collaboration [111]. They contribute towards creating a shared understanding and connecting people and places. At the same time, catering to the needs of a heterogeneous group of people requires finding a balance between well-embedded, unobtrusive yet explicit enough and recognizable interface designs that do not disrupt non-interested user groups [41, 46]. Urban interfaces complying with both challenges should, thus, be 1)

Authors' addresses: Linda Hirsch, linda.hirsch@ifi.lmu.de, LMU Munich, Munich, Germany, 80539; Marius Hoggenmueller, marius.hoggenmueller@sydney.edu.au, University of Sydney, Sydney, Australia; Ceenu George, ceenu.george@ifi.lmu.de, University of Augsburg, Augsburg, Germany; Louisa Bekker, lou.bekker@campus.lmu.de; Sarita Sridharan, sarita@sridharan.com; Andreas Butz, butz@ifi.lmu.de, LMU Munich, Munich, Germany, 80539.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.
© 2022 Association for Computing Machinery.
Manuscript submitted to ACM

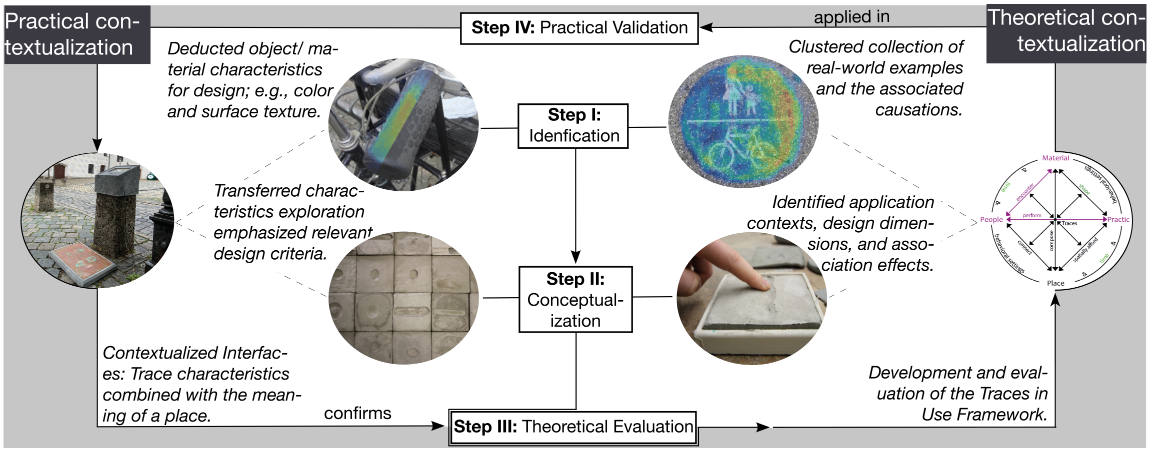


Fig. 1. Our iterative design approach to develop and evaluate the *Traces in Use* design concept presented in this work.

culturally and socially contextualized so that they support users' engagement and connectedness to a place [22, 53, 54], and 2) physically and spatially embedded into the environment to enrich the place's atmosphere without interrupting it [46, 53, 108, 115].

To find approaches that tackle both challenges, we present the ***Traces in Use*** design concept. It aims to address the challenges mentioned above by turning natural traces of use characteristics into interface design features for interaction. We build on previous research on material traces and, more specifically, *traces of use*, which are defined as discernible changes in the material caused by recurring direct or indirect human interaction [33, 86]. Such traces – for example, the squished teddy bear passed on through family generations [99] – provide evidence of personal relationships between users and objects. Prior work has discussed the traces' potential to influence a place's socio-cultural meaning and spatial affordance in public, urban environments [3, 42, 85]. However, the current state of the art has yet to explore material traces in the design of contextualized interfaces to create shared experiences and understanding in public contexts [44]. Similarly, guidelines or design dimensions for creating traces as a design element in interfaces are limited. This makes them difficult to design and evaluate. Therefore, we explicitly highlight the distinction between natural, urban traces of use and the design concept presented here, *Traces in Use*. The concept consolidates, abstracts, and processes the identified characteristics of natural traces of use and ignores confusing and negatively associated characteristics such as accidentally caused scratches (see Table 1). We propose *Traces in Use* as a design concept applicable by designers across different situations, technologies, and contexts to foster users' sense- and meaning-making and interface contextualization.

We explore and refine the role of traces in design by approaching questions such as: Can natural traces of use be turned into a design concept to contextualize urban interfaces? What are the types and characteristics of natural traces of use that contextualize urban interfaces? And how can we design and implement traces as control elements for tangible urban interfaces to foster users' meaning- and sense-making while supporting a place's atmosphere? We explored these questions in a four-step iterative process as presented in Figure 1. Notably, these steps and their results also guide the structure of this work and are denoted next to each chapter:

Step I Identifies traces of use as potential design elements to create contextualized interfaces. Clusters traces of use types, their meaning, and characteristics natural for public urban environments (N=4 and N=52).

Step II Together with Step I results, this step provides the basis for the *Traces in Use* design concept and introduces design consideration when applying it. Transfers characteristics identified in Step I to concrete artifacts to evaluate the traces' understandability, effect on the interface affordance, and user perception in an elicitation lab study(N=33).

Step III Confirms and develops the concept on a theoretical basis and contributes a *Traces in Use* framework that incorporates all dimensions and relationships relevant when designing contextualized *Traces in Use* interfaces. Evaluates the framework and the derived concept theoretically in expert interviews (N=8).

Step IV Validates the concept and the framework on a practical basis: (a) Applies the framework and the concept in practice in the design process of three contextualized urban interfaces. (b) Tests the interfaces in two empirical field studies (N=40).

Our results show that the *Traces in Use* design concept promotes contextualization while complying with the needs of heterogeneous user groups. In particular, it fosters social and cultural understanding and the connection to the local identity and provides a suitable means to embed interfaces physically and spatio-contextually. The *Traces in Use* framework provides a supportive tool before, during, and after the design process of the contextualized interfaces. Yet, it is a theoretical framework that requires the application of complementary tools and methods (e.g., the meaning of place framework [37] in Step IV).

Altogether, our work defines and evaluates the design concept *Traces in Use* on a theoretical and practical level using an iterative, mixed-methods design approach. We contribute a comprehensive overview of the iterative concept development, from identifying natural traces of use characteristics to the *Traces in Use* concept's evaluation in public urban places. Furthermore, we show the making process of tangible interfaces incorporating the *Traces in Use* concept along three interfaces and their making, applying a *research in* and *through design* approach [16]. Lastly, we also emphasize the potential to apply the concept in other contexts and realities (augmented, AR, and virtual reality, VR).

2 RELATED WORK

This section gives a short overview of prior work on contextualizing urban interfaces to foster sense- and meaning-making for diverse user groups. We then outline previous work that explored traces of use in the physical world context, including projects from materials experience design and spatial navigation. Lastly, we present usage examples of traces in digital and virtual world contexts for delimitation and discussion purposes.

2.1 Contextualizing Interfaces for Sense- and Meaning-Making in Urban Contexts

To achieve contextualization of public interfaces, the Urban IxD community has increasingly expanded their design practices toward considering the notion of sense- and meaning-making, which means designing urban interfaces that are socially relevant [111] and valuable to individuals [82]. Sense-making is the process of connecting the experience beyond the interaction, whereas meaning-making allows for the creation of concepts and relationships [72, 114]. Vande Moere and Wouters [103] introduced three intertwined perspectives that should be considered when contextualizing interfaces, namely the content, carrier, and environment, that would allow creating interfaces of personal relevance and meaningfully linked to the local community [102]. Over the years, Urban IxD research began to scrutinize its *"message"* and *"purpose"* [29]. To increase meaning and sense of place, researchers explored, for example, bottom-up approaches and

DIY practices that support placemaking and citizen participation [10, 14], or weave in theatrical and narrative elements to promote cultural and heritage conversations [25, 47, 109]. It requires exploring alternative approaches for integrating digital media and interfaces into urban environments because they require the user's constant visual attention [106] and neglect architectural intentions [113]. The latter can lead to a contextual disconnect with the surrounding environment, resulting in disregard or even vandalism by the public [103]. Approaches include, for example, the use of low-resolution lighting displays (e.g., [63, 80, 94, 107]), the manipulation of physical materials to represent digital content [49] or the use of urban robots to create chalk-based urban displays [48]. Yet, the contextualization of urban interfaces is an ongoing challenge requiring further research and explorations [103, 108].

2.2 Traces and Similar Concepts in The Physical World

For decades, researchers have studied design concepts similar to traces of use in the form of "social traces" [93], "markers of experiences" [86], "worn patches"[67], or "temporal patterns" [89]. There are many overlaps among these concepts. Yet, it is currently intransparent what the common underlying concept is, including a lacking clear understanding of the traces' effect and application potential. We attempt to create such a consolidating concept based on traces because they are evidence of prior interactions triggering associations and meanings to or from a material [86, 89], an object [67, 98, 99] or a place [44, 77]. For example, Rosner et al. [89] discussed material traces of use using the cracks in a plate derived by usage as anchor points to connect digital stories to the objects. In another work, Tsai and van den Hoven [99] looked into personal objects and their traces of use. They found that an individual, subjective perspective on the traces provides higher emotional connectedness and reminiscences than an objective, third-person perspective. Traces are also applied to reveal and communicate common behavior or movement patterns [24, 40, 88, 112]. For example, Rogowitz et al. [88] visualized traces of use to identify main touch areas and behaviors that museum visitors would manifest at art pieces. In contrast, Hespanhol and Dalsgaard [40] discussed traces of use as a design strategy to visualize spatial movement patterns through digital means in urban environments. Another work introduced the *natural traces of use* design strategy [45] to embed interfaces into the public seamlessly, urban environment due to their recognizability, ubiquity, and naturalness [7, 44]. Particularly traces dealing with physical traces of use emphasize their dual functionality of changing an interface's affordance and incorporating socio-cultural meaning. Hummels and van Dijk [56] and van Dijk [101] explore traces in collaborative scenarios. They define traces as design features that support embodied sense-making [101] and enable users to understand what others have done [56]. Considering the examples above, traces of use in design can be defined as social signifiers, which are meaningful social cues embedded into an environment [61, 79]. Norman [79] introduces, for example, a bookmark as a social signifier because it indicates how much the reader has proceeded in the story. However, the currently discussed social signifiers mainly relate to object positions within a (physical or digital) environment and have yet to consider the role of material experiences. It is outstanding how much traces of use and social signifiers interlink. The examples above also show that traces can foster sense- and meaning-making but have not yet been explored in the contextualization of urban interfaces.

2.3 Traces in Online and Virtual Worlds

Although not specifically named as such, traces of use are also applied and explored in digital and virtual contexts. We consider online search and activities as digital contexts, which often gather digital traces of use for analysis [4, 65] and recommendation purposes [55, 105]. Prior work defines any traceable record of human interactivity as digital traces, including activity information, online posts, or profiles [65, 95]. In contrast to physical world traces, digital traces are often invisible to the users who cause them. They are not linked to, for example, worn-off, decomposing materials [66] but accumulate to behavior patterns [64] that are shared with system designers and data analysts only. Thus, digital traces are often detached from their users, which also shifts their ownership from the user to a third party. Nonetheless, they are also used to generate understanding and connectedness [35, 105]. Grover and Mark [35] increased understanding for their users by deriving users' personality types based on the temporal, digital traces generated through smartphone and personal computing device usage. In another example, Wei et al. [105] connected users by suggesting group event recommendations based on individual users' digital traces.

In Virtual Reality (VR), researchers similarly use traces for analysis purposes [38, 83] and to increase social presence and awareness [12, 43, 92]. Patney et al. [83] tracked gaze traces through eye tracking to improve the rendering of VR. Furthermore, Chow et al. [12] found that traces of use increase social awareness and presence in asynchronous collaborative work environments. Their traces are reflected in the form of moving virtual objects within the shared virtual office requiring users to remember the previous position. Similarly, we [43] explored four types of traces of use deriving from physical world design research [6]: i) object (non-reversible) characteristics, ii) object's (reversible) states, iii) object settings, and iv) object context. The study confirmed the traces' positive effect on asynchronous social presence and awareness in shared VR, which agrees with the physical world traces' design potential of increasing socio-cultural connectedness and fostering understanding. However, their nature significantly differs as they are purposefully designed and only partly accessible for background system processes, and not their users.

2.4 Summary

Traces of use can foster sense- and meaning-making in an individual and shared user(s)-object relationship(s). They can implicitly and calmly embody meaning on a personal, social and cultural level. This motivates us to research their effect and potential to contextualize urban interfaces. Nonetheless, the projects mentioned above also show traces' versatile and divergent characteristics and application contexts, which currently make them a fuzzy concept to grasp and apply for design. Consequently, we develop the *Traces in Use* concept by first identifying and clustering urban traces of use examples and their characteristics (Step I [44]), and second, exploring their making and effect in a context-independent lab study (Step II [45]). Based on the results, we developed a framework in expert interviews (Step III), which we further evaluated in the design process of three contextualized urban interfaces (Step IV).

3 CONCEPT DEVELOPMENT [STEPS I + II]

Step I and II identify the potential of natural traces of use originating from urban environments for contextualizing public interfaces. They provide the basis for the *Traces in Use* design concept. We developed the concept iteratively by mapping natural urban traces of use analogies to interface designs. The approach was inspired by structure-mapping, which is the cognitive process of recognizing similarities and drawing relations from a natural entity to a design feature [23, 71, 90]. In Step I, we collected pictures of 182 different traces of use examples in the public, urban environment to identify common and recognizable trace characteristics. We clustered and evaluated the collection with a focus group (N=4) and an online survey (max. N=52), resulting in the identification of recognizable, and appreciated versus disliked trace characteristics. This step is based on prior published work [44]. In addition to the published content, we provide more details on the experts' discussion and summarize the overarching findings of Steps I and II. In Step II, we explored the identified trace design features in an interface made of concrete, an abundant material in urban environments. We compared two approaches to create the designs, one abstract and one natural. The aim was to change the concrete's affordance from a non-interactive to a seemingly interactive material for touch interaction and to explore the transfer and limits of trace characteristics for interface design. We tested the interfaces in an elicitation study (N=33). This step is based on published work [45].

Below, we present the approach and methods of each investigation. We mainly focus on the identified trace types, their characteristics, related associations, and elicited affordances that we identified relevant for including or excluding in the design concept. For more details on the approach, please refer to the published works [44, 45]. We contribute design considerations based on the identified traces' types and characteristics in both steps, presented in Table 1.

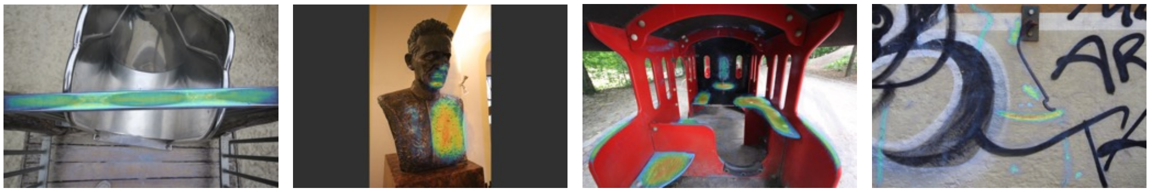
3.1 Identifying Traces of Use Characteristics For Design [STEP I]

In public environments, physical traces or changes in material conditions can derive from various causes, such as weather influences, animals, machines, or humans. We report how trace examples from our collection are perceived in a focus group and an online follow-up survey and highlight relevant trace characteristics.

3.1.1 Focus Group. We preselected 46 of the 182 pictures that differed in the types of traces and locations as a discussion basis for the focus group. The preselection was conducted in a brainstorming session between two authors who aimed to create a picture set including a variety of types of traces, traces' positions in context, and locations. The focus group consisted of four experts: two architects (A1 and A2), one industrial engineer (IE), and one philologist (P). Participants discussed the picture set regarding the making and effect of the traces from urban architecture, from both societal and anthropological perspectives.

3.1.2 Focus Group Results. The experts clustered the pictures into eight themes: 1) Negative unconscious, 2) Accident, 3) Indifference, 4) Nice that it is used, 5) Positive Conscious, 6) Scratches, 7) Patina (a material aging effect over time and use), and 8) Lanes. These themes related partly to the action causing a trace (e.g., *accident*), associations about the person that caused the trace, or the trace's effect on an object's appearance and meaning. Additionally, participants discussed the purpose and limitations of traces of use in public, urban places. For example, herd paths have been used in history to navigate and find meeting places; *"That people always take the same path is also important to find the places"*, P. Another influencing factor on the meaning and role of the trace would be the spatial setup and affordance by considering how shared places are used and what type of traces result from the interaction (e.g., *"you don't really have so much space to walk anymore and everyone drives by car"*, A2). Regarding the associations triggered by the traces, the participants agreed that context essentially influences meaning-making and a sense of ownership. A1 explained *"If I now see, for example, that a pavement slab on the street is broken, then that's something I just see. That's just the way it is. If I now see that a pavement slab in my driveway is broken, I would say, we have to do something about it"*. Besides whether the traces occur in a public or a private environment, the experts agreed on the important differentiation of whether the traces resulted from a conscious or unconscious and direct or indirect interaction. They often linked indirect interactions to unconscious behavior, which was negatively perceived. In contrast, they saw potential in using traces to support navigation or indicate the shared use of places and objects.

3.1.3 Online Survey. We followed the focus group up with an online survey asking participants (N=52) to mark the traces of use on 18 pictures for recognizability. The picture sample consisted of two photos per identified cluster plus two ambiguous pictures that had not been sorted. Participants had the chance to leave pictures out if they did not recognize any traces of use. We visualized the commonly recognized areas with a Processing [30] script and applied the turbo scale for histograms to create heatmaps.



(a) (b) (c) (d)

Fig. 2. Heatmap examples: a) handle at the start of a slide in a playground, b) statue with rubbed-off parts, c) material differences at a playground, and d) sprayed and scratched wall.

3.1.4 Results. Overall, we found traces of use well recognizable in urban environments. Strong contrast in color, material texture and consistency facilitated their identification. In contrast, noisy surroundings with multiple traces or unfamiliar objects made it harder to create commonly identified areas (e.g., Figure 2(a) and Figure 2(d)).

3.1.5 Summary & Discussion of Step I. Traces of use are ubiquitous in and natural characteristics of urban environments. Our results showed that they are well recognizable, particularly regarding seven trace characteristics that can be explored for interface design: 1) texture, 2) color, 3) depth, 4) shape familiarity, 5) cultural context, 6) patina, and 7) weathering versus human traces of use. Each distinguishes a trace from the object and contributes to its meaning and associations. However, the associations linked to the traces differed according to where they appeared and who caused them through what interaction. For example, Figure 2(c) shows parts of a playground where traces of use are derived through children playing. Accordingly, these traces were associated with positive, joyful situations.

Traces representing conscious and purposeful behavior that contribute to the historical atmosphere of a location or an object were appreciated. We also want to note that the picture sample was limited. We have yet to identify an exhaustive set of trace characteristics and types but see it as a starting point to explore traces of use for Urban IxD. In the following step, we summarize how we explored the material traces of use along interfaces made of concrete.

3.2 Exploring Traces of Use For Interfaces Made of Concrete [STEP II]

Considering the aim to contextualize urban interfaces, we were interested in how the traces would change an urban interface's affordance and participants' sense-making. We selected concrete as the interface basis because it is a ubiquitous urban material and is mostly known to be non-interactive, which allowed us to explore the immediate effect of the traces on participants' mental model. Additionally, we selected concrete considering the need for calm, embedded interfaces that seamlessly blend into the environment [11] and allow for direct interaction with the built environment [60, 107].

3.2.1 Study Design & Participants. We created three commonly applied UI elements, a button, a slider, and a scroll wheel in concrete (see Figure 3). Each UI element was created in two versions: The first design approach closely reassembles the natural traces of use characteristics, called the *natural design* approach, whereas the second uses the same features but as a stylized analogy, namely the *abstract design* approach. The natural design included rough and irregular shapes, strong texture differences, and slightly ergonomic outlines as if deriving from an actual touch interaction. In comparison, the abstract designs consisted of clear, symmetric shapes representing highly abstracted traces of use. Figure 3 provides an overview of all study pieces. Transferring the findings from Step I, we focused on texture, shape, patina, depth

Fig. 3. Traces implemented in concrete interface control elements through real-world inspiration.

difference, and surrounding weathering. We deliberately decided not to explore colors at this stage so that we could focus on the textural and structural material first. Also, we purposefully conducted the study in the lab to avoid any confounding factors, such as influences of the surrounding environment or cultural context, which might have affected the participant's meaning-making.

We evaluated our designs in a within-subject touch gesture elicitation study (N=33) combined with a questionnaire for each interface element and one final questionnaire comparing the two design approaches overall. We analyzed the number of differing, selected terms per concrete element and the most-selected terms of counterparts. Additionally, we conducted significance tests on survey results and a thematic clustering of interview responses. 33 participants (age range: 18 to 48 years, gender: 14 self-identified as female, 19 as male) completed the study.

3.2.2 Results & Discussion Step II. Both design approaches influenced participants' opinions of concrete as an interactive material. 21 participants said they generally enjoyed interacting with the concrete elements and were curious to touch and explore them. Two participants completely refused the idea of concrete as an interface, while the remaining 10 were indifferent. 13 participants preferred the natural designs, 19 preferred the abstract designs for touching, and one stayed undecided. About the natural designs, they appreciated the natural and organic look, the greater freedom of use, and the ergonomic shapes. Additionally, the designs would trigger a higher level of interest and a desire to explore due to their irregular shapes, e.g., *"If it looks natural, but you still see that it is artificially made then it looks interesting, then I want to touch it."*, P9. Several participants related the natural designs to previous interactions with others due to the shapes and the patina effect. They considered this encouraging to interact with a material normally known as non-interactive; *"It encourages you to do it, simply because others have already used it."*, P12. However, the weathering and irregularities also decreased the natural designs' aesthetics and perceived hygiene, which reduced participants' willingness to touch them. Too irregular textures and depth differences also caused participants to treat those as push buttons, triggering confusion rather than helping the understanding. Accordingly, traces can also reduce interface affordance, requiring a careful balance of their naturalness and abstraction. Nonetheless, participants could imagine integrating the naturally designed concrete interfaces into public environments, for example, playgrounds, statues, museums, and display controls. They related interactions, such as explorations, discovering, and connections to others, to the natural trace designs. In contrast, participants liked the abstract elements' geometric, clear, and defined shapes. They enjoyed the smoother surface texture and felt a stronger sense of movement control. Additionally, these

Table 1. Types of traces and deducted design considerations based on Step I + II. We summarized types where possible.

Picture Example	Types	Agreements by Participants	Design Consideration
	**Accident, Negative Uncon-scious**	Accidentally and indirectly caused object changes reveal negatively perceived unconscious, unintended behavior.	clearly communicate the purpose and intention of the trace design; avoid cracks.
	**Indifference**	Traces on non-personal objects appearing rather outside the focal point or are surrounded by a lot of other traces do not trigger meaning but are easy to ignore.	Avoid too noisy trace designs but emphasize one trace that stands out from its surrounding. Place the traces on objects relevant to the user.
	**Nice that it is used**	Traces on positively associated carriers and practices such as riding a bicycle trigger sense- and meaning-making.	Consider carrier, practice, and material choice in dependence of each other connected through the trace.
	**Scratches**	Scratches are seemingly unavoidable traces that naturally happen over time, yet, they are rather negative evidence of use.	Add scratches for a natural appearance; avoid them if possible.
	**Traffic Lanes**	Traces linked to the dissolution of a familiar shape are recognizable, yet it remains partly unclear whether they were caused by human interaction or not.	Clearly differentiate between weathering and human traces; explore alterations / dissolution of familiar shapes.
	**Positive Conscious**	Traces linked to conscious, purposeful interactions were associated positively and can reflect cultural customs.	Create purposeful traces by reflecting familiar touch gesture traces from, e.g., cultural customs.
	**Patina**	Traces slowly deriving over long-time, and -use represent authentic signs of social behavior patterns of, e.g., a community and their history and contribute to a shared place's atmosphere.	Replicate the patina effect in the form of smooth, even surfaces simulating rubbed-off material yet intact objects.

designs were easier to understand and communicated a clearer intention of usage; (e.g., *"with the more abstract ones you see that it is on purpose"*, P31). However, due to their simplicity, they were also considered less interesting and little thought-provoking. Nonetheless, participants could imagine having such concrete elements embedded into their homes to control, for example, the light, music, or an elevator as they *"fit well into the architecture"*, P17.

3.2.3 Summary Steps I + II. Step II identified criteria from Step I that need balancing due to their essential influence on the understandability and meaning of the traces and their carriers. This includes considering surrounding conditions and the place in which an interface would be located, and selecting either a natural or abstract trace design. Participants' qualitative feedback agreed that the abstract design is more suitable for indoor contexts and the natural one for outdoor environments. Yet, the natural design requires reducing irregularities and too extreme characteristics as those rather confuse and distract (e.g., pushing bumps by understanding them as buttons). Furthermore, the understanding is further influenced by users' expectations and intentions – the abstract design approach supports simple, familiar, and direct interactions, whereas the natural design seems more engaging. In contrast, the natural designs' patina effect and the ergonomic shapes triggered associations about other, prior users and their interactions. It adds a social component that may assure users of an interface's interactivity and trigger their curiosity to interact similarly. This resembles and could be referred to as a 'detached' form of the honeypot effect, which originally describes the phenomenon of people being stimulated to interact with an interface after seeing others interacting with it [112]. Altogether, we identify the relevance of balancing the trace characteristics to increase the interface affordance and create the connection and understanding of prior interactions. We present an overview of the traces' types and characteristics and deduct design considerations in Table 1 consolidating findings from Steps I and II. Both steps show that the context is essential for the traces' meaning-making requiring considering the place (**Place**), who (**People**) uses it, and how (**Practice**) throughout the design process. We use these identified design dimensions to create a *Traces in Use* framework (see Figure 4) and refine the *Traces in Use* interaction design concept.

4 TRACES IN USE FRAMEWORK – [STEP III]

We developed the *Traces in Use* framework to provide designers with a theoretical foundation when applying our design concept. It includes all components believed to influence the sense- and meaning-making of the traces and their user experience. The framework was originally published in Hirsch et al. [43] as the *Traces in VR* framework, focusing on implicitly increasing social presence and awareness in virtual environments. However, the framework is part of a larger research project aiming to translate natural traces of use into a generalizable *Traces in Use* concept for both realities, physical and virtual. To validate the framework for physical traces of use, we conducted additional interviews with urban and interaction designers, using and researching traces in the real world. To avoid any bias and increase internal validity, we followed the same interview protocol regarding the introduction to the framework and questions as with the VR experts [43], i.e., asking them about whether they know and apply similar concepts and how they could imagine that our concept could support their research. We share the anonymized transcripts and the coding scheme via osf.io[1].

A thematic analysis of the interviews confirms the framework for the physical reality thereby validating our prior results. Yet, the items in the framework itself are interpreted differently in the virtual vs. the physical context, which we detail below. As this paper's focus is on physical world traces for the contextualization of tangible urban interfaces, the differences between virtual and physical realities are beyond the scope. However, we dedicate a paragraph in the discussion linking our findings from the physical to the digital and virtual realities. In this section, we present the development and rationale behind the *Traces in Use* framework and its evaluation in eight expert interviews for the physical reality. The interviews resulted in the iterated framework shown in Figure 4 with changes highlighted in green. We also interviewed experts about the concept, asking them how and for what they would use and how they would integrate it into their design processes. Overall, we evaluated the concept and the framework, first on a conceptual and

[1] https://osf.io/zgkfq/?view_only=73313405ba13423bba8c0afdb000cc8f

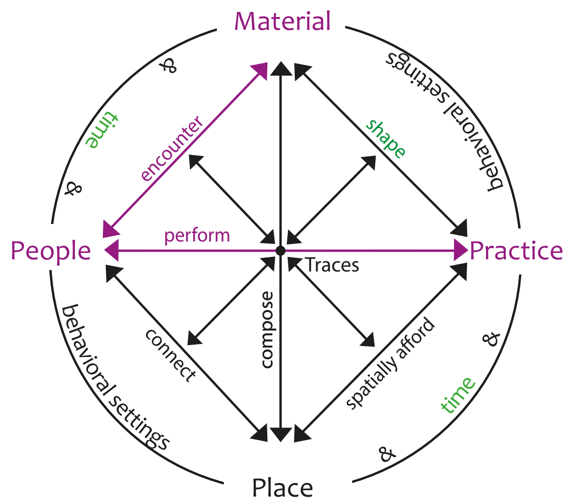


Fig. 4. *Traces in Use* framework: The purple color reflects the materials experience design framework that this framework is based on [33], and the green color indicates changes after the expert evaluation.

theoretical level in the expert interviews, and second in a situated design research project creating three contextualized urban interfaces in Step IV a+b.

4.1 Framework Dimensions and Relationships

We developed a framework with *Materials*, *People*, *Practices*, and *Places* as the main design dimensions that influence and are influenced through traces. It is based on the materials experience framework iterated by Robbins et al. [86], who defined traces as a design approach that shapes the socio-ecological context between people, materials, and practices. Aiming to counteract users' increasing lack of engagement with technology, understanding, and socio-emotional connectedness, their work shows the traces' qualities of revealing the relationships and enabling bi-directional communication between these dimensions. As presented in our prior work [43], we extended their framework to include *Place* as another main design dimension and *Behavioral Settings* as an overarching dimension. *Behavioral Settings* represent the users' personal, cultural, and societal backgrounds that influence their sense- and meaning-making of the traces and the urban environment [3, 42]. Our results in Step I and Step II further confirm the *Place* and *Behavioral Settings* dimensions because of the contextual dependency that influences how traces are perceived and interpreted (i.e., situated in a playground context versus a parking lot; a rubbed off statue versus a broken motorcycle). We added the *Time* dimension and renamed the *collaborate* relationship into *shape* after the interview evaluation as highlighted in green in Figure 4. Within the framework, the traces are purposefully positioned in the center because they communicate and reflect the relationships between the dimensions. In line with Robbins et al. [86]'s work, we argue that the traces enable users to create meaningful connections, supporting their sense- and meaning-making. We introduce each dimension and relationship in more detail below.

4.1.1 Dimensions: The *People* dimension comprises users encountering the other dimensions through traces. They may be passive bystanders, passers-by, or active creators that leave traces behind. There can be one or many people simultaneously with different intentions and interests, just like the heterogeneous (non-) user groups of public places [41, 46]. *People* further represents the personas creating the meaning of traces on an individual, shared, or communal level. The *Material* dimension refers to the carrier of the traces, its materials, and its characteristics. Physical traces are tangible and are reflected in varying shapes, textures, and other material characteristics. They can also be purely visual [26, 87], or auditive (e.g., movements turned into sounds [89]) depending on the material they are made of. *Practice* refers to "ways of doing" [33] in the form of daily practices and routines. These can be one-time (e.g., accidents, such as a bent stop sign; see Table 1), accumulated (e.g., used furniture), or intangible interactions (e.g., showing the frequency of use in the form of a heat-map). The dimension *Place* frames the physical, architectural, and spatial conditions that provide the surrounding environment of an interface. Meaningful social encounters characterize an interface [21] by embodying and communicatinig their users' experiences, prior happenings, and cultural norms. Places can be public, semi-public, or private depending on, for example, access restrictions, ownership, and type of relationships between place users (i.e., [15, 28, 91]). Accordingly, the socio-cultural setup strongly defines places' meanings and characters. The outer circle of the framework denotes influencing factors that affect the interpretability of traces for each of the connected dimensions, namely *Time* and *Behavioral Settings*. *Time* summarizes the natural temporal development of a trace deriving through the communication and encounters between the dimensions as well as the developments of each individual dimension [44, 66]. People's cultural and personal backgrounds and their experiences onsite influence, for example, how places become meaningful and are used.

4.1.2 Relationships: The axis in the middle of the framework refers to bi-directional connections between the dimensions *People*, *Place*, *Practice*, and *Material* [110]. Similar to the material experience framework according to Robbins et al. [86], ours highlights that initial encounters with materials influence people's expectations and judgments of traces. Independent of whether a place is private or public, they connect people socio-culturally, and people connect to places on an individual and communal level. They also afford certain practices similarly, like practices that can change a place's spatial affordance. Also, places compose materials and objects and vice versa. In accordance with the bi-directionality of the actions, practices can change a place's affordance and shape the material over time, generating traces of use.

4.2 Expert Interviews

We conducted eight semi-structured interviews, four with experts in urban interaction design (UIxD experts) and four with experts who had one or more HCI research publications about traces as design features (traces experts). Five self-identified as male, and three as female. The average number of years of experience in their area of expertise was nine (*SD* = 5). We recruited the participants partly via our institutions' network, and partly via a snowballing approach, i.e., through recommendations from our interviewees. Interviews were conducted in English and took about 30 minutes each. All experts participated voluntarily without receiving any compensation.

4.2.1 Interview Process & Analysis. We conducted the interviews via zoom [116], beginning with an introduction to the *Traces in Use* concept and the framework. All participants gave their consent to record the sessions and store and process the data under GDPR [1]. We used GoTranscript [68] to transcribe the interviews. Two researchers independently coded them thematically using condens.io [34] and miro [76]. We followed the inductive approach by Braun et al. [9], which includes six steps: 1) careful familiarization with the transcripts, 2) creating the first codes, 3) clustering them into themes, 4) revising the themes, 5) finally defining the themes, and 6) consolidating and documenting the findings. It took three iterations until data saturation was reached, including three main themes, seven sub-themes, 20 sub-sub-themes, and 163 individual codes. No codes exclusively occurred in one area of expertise among all experts. Accordingly, we present the overall interview results instead of separating the areas of expertise.

4.2.2 Results & Discussion: CONCEPT. The *Concept* theme clusters all points to the concept's and the traces' universal meaning and application potential. According to our experts, traces can create and strengthen meaningful relationships between humans and individuals and interfaces. For shared contexts, the concept could support more-than-human design [27, 104] by including other living- or autonomous beings and their traces, such as for example, birds or robots. In another direction, the experts discussed the long-versus mid-term effect of traces in shared environments; *"more short term trace creation where it's a much more vivid shared memory, [that] can be another way to make [...] you collectively part of when those traces were created [...]. Looking at those large collective memories or collective experiences and traces that result in all or relay back to that instance."* (traces expert 2). Using traces to foster shared experiences and create collective memories creates value and strengthens self-identity. Additionally, the experts said that the concept could support the preservation of historic artifacts and sites through user participation when considered in the design process. Considering these different potentials, the *Traces in Use* design concept could contribute to increasing the cognitive and emotional attachment between users and the data processing in the background of an interface.

4.2.3 Results & Discussion: TRACES. The theme *Traces* included five sub-themes and 19 sub-sub-themes.

Design. This sub-theme comprises all sub-sub-themes related to the *Design Requirements*, *Intentions*, *Challenges*, *Opportunities* and *Considerations*. The *Intention* to design with traces is based on either aiming to increase the meaningfulness of an interface or, fostering embedded and embodied interaction in place. It relates to the design *Opportunities*, which affirms what traces can be used for. For users, the experts emphasized community building through the perceptibility of mass behavior and the embodiment of other people's (digital) traces. At the same time, it allows for a certain ambiguity in the interpretation. Furthermore, the experts discussed the traces' implicit effect, which could be used to design unobtrusive interfaces and peripheral interaction; *"It's your choice to listen to them and engage with them. So to talk to you if you want to learn from these narratives or these traces that have been left around."*, UIxD expert 4. In contrast, they can also be used to increase the affordance of an interface and its utility or to reveal designs that are differently used than originally intended: *"people taking shortcuts and that creates these paths. That gives you a very good indication [...] that your design was, um, yeah, not the greatest."*, UIxD expert 3. Five of our experts used traces for analysis purposes and to evaluate, for example, movement patterns in the shared space.

The *Challenges* include, for example, designing interfaces that also persist in meaning for long-term usage. Any changes or external influences risk changing the traces' meaning, making it hard to account for eventual developments in advance. Another challenge derives from the exclusivity that digital traces particularly entail. As soon as they are only perceptible by a certain user group, there is information withheld from others. Traces generally consist of various characteristics (color, depth, shape...), making designing them complex and challenging. Additionally, the traces can also dissolve or disappear within the mass of traces, confirming the too noisy surrounding in Steps I+II; *"If we have too many different traces I can't really identify the ones really meaningful for me or personally attached to me, um, especially in those community places where [...] there will be a massive amount of them."*, traces expert 3. It requires curating the traces to enable effective and quick identification. We summarize such requirements in the sub-sub-theme *Requirements & Considerations*. Designers face the responsibility to accommodate unknown influences and communicate such complex intersections understandably to users. One suggestion is rooted in explicit materials experience by, for example, using strong visual contrast. Yet, the traces' effects must be balanced and adapted to the context to trigger meaningful associations of common understanding and not divert from it. This makes designing *Traces in Use* interface very complex and challenging.

Nonetheless, designing with traces facilitates turning everyday objects from *Carriers* into *interfaces* by changing the object's material affordance and giving them meaning beyond the pure interaction. This confirms Step II results. Similarly, they influence the spatial design and affordance of an environment (*Influence on Place*), which can further influence a user's feeling of ownership of a place. UIxD expert 4 gave an example of a location-based sound trace that changed users' understanding and connectedness to the place and to the other people who had left the sound trace; *"It almost felt like I was them. And then [...] I have an understanding of what their experience was like viscerally and an embodied experience of that"*.

Effect. Besides increasing affordance and meaningfulness, traces can also increase trust, attachment, and personalization through the *Connection to the Interface*. The traces expert I even stated that traces make the individual experience better over time, referring to shoes and digital traces as examples: *"Shoes are my favorite example. I mean, they start really stiff, and it's the breaking in that makes them work better. And that's the same with the digital traces"*. At the same time, traces can also foster *Understanding* and socio-cultural relationships, particularly traces in shared public places. As others then create the majority of traces, they instinctively increase social awareness and allow for assumptions about past happenings and a place's history. History is a shared history, embodied through traces that can create a bond; *"[...] a broader group of people rather than individuals, [...] it might be a little bit more, um, easy to get that strong connection or that link between say memories and traces*", traces expert 2. Additionally, traces can trigger curiosity and invite us to explore. The sub-sub-theme *Movement & Physical Changes* summarizes the physical traces in the environments, such as material changes in space or movement patterns, and the role of traces in encouraging movements. For example, UIxD expert 2 talked about a project comparing two interface versions, one more prototypically appearing and the other more finished looking. The prototypical version arrived with more interaction because the finished version *"[...] drew less attention and was used less because, I think, they're thinking that it looks more permanent now. So, people already kind of put off their interaction"*. This effect relates to the "detached honeypot effect" identified in Step II because it would trigger people to interact due to associating how others had interacted with it before. It emphasizes the bi-directional relationships of material characteristics affording certain interactions and interactions changing the material qualities.

Meaning. This theme comprises the differences in meaning of traces for *individuals* and *shared* groups, and *common influences*. In one-to-one (user-to-object) relationships, the traces can represent an intimate, personal situation and often serve as memory cues that trigger reminiscence and self-reflection; *"memories [...] associated with someone's sense of self, or, their identity and therefore quite personal memories"*, traces expert 2. In contrast, *shared* meaning was always mentioned in the context of shared understanding, history, and community. However, experts also found it harder to design for it because shared contexts increase emotional distance. *Common influences on meaning-making* comprised the dependencies of traces on their desirability, ambiguity, a user's behavioral settings, and imagination skills. Furthermore, their meaning is influenced by the social relationships between the user and others.

Characteristics. We split *Characteristics* into six sub-sub-themes, *Digital*, *Physical*, *Temporal*, *Perceptibility*, *Missing or Wrong Traces*, and *General Characteristics*. *Digital* traces are defined by design and implementation. They often stay invisible to their users and only communicate with certain groups. This leads to a loss of users' autonomy. Yet, they also extend their functionality by providing users with, for example, more personalized recommendations. The experts defined algorithms as digital materials that contribute to creating a narrative through traces: *"It's not only humans that have that agency, and that capacity to create change and impact and trace upon the environment, but it's also these non-human things, like the materials of the AI, or the code, or whatever"*, traces expert 1. The personalization effect can further lead to digital placemaking. Besides, digital traces can be used to create spatial heat-maps through, for example, eye or head tracking. Lastly, they support the impression of being in virtual environments by reflecting physical world characteristics in the digital world.

With *Physical*, we cluster trace characteristics that are grounded in the tangibility and physicality of the physical world. Our experts saw physical traces also as embodied, enduring memory: *"I can see there's a memory, I mean, stored in the traces, a memory about the previous users and also the memory about the social interaction, and a trace has been left on this kind of objects"*, trace expert 4. At the same time, traces evolve and are transient, representing a physicalization of time (*Temporal*). Ephemeral traces have a shorter lifetime than persistent traces, which makes digital traces often ephemeral to their creators. In *Perceptibility*, experts discussed that traces are rather attention-inviting than demanding and, thus, contribute to balance information overload. At the same time, the discussion resulted in open questions about what information should be presented through traces and what should stay hidden from users. One of the considerations in the decision-making relates to the traces' aesthetics and their influence on the aesthetics of the surroundings, which *"some people probably don't want to see"*, traces expert 3. It intertwines with the sub-sub-theme *Missing or wrong traces*, in which people also erased others' traces (*"so this person took control of, of the area to [...] get rid of traces"*, UIxD expert 3) because of personal dislike. Similarly, there are traces that go unnoticed or result from wrong usage (for example, scratches). Yet, the lack of traces would lead to a lack of reflection and meaning.

The *General Characteristics* comprise four trace classification criteria: 1) human versus non-human, 2) intentional versus unintentional, 3) accumulated versus instance, and 4) abstract versus natural. Similarly, experts defined them as evidence of meaningful experiences and relationships, as a consequence of practices in places, as evidence of historical significance and authenticity, as nudges, as the embodiment of entanglements, and as natural features of environments and objects. Additional to the classification and definition, experts shared examples of audio and robot-specific traces. The latter emphasized the need to design traces that are characteristic of their causer.

Research Potential. The interviews revealed further research potential regarding evaluation methods and exploring the traces' design potential. Current methods to measure meaningfulness and different types of meaning are mainly qualitative, with no known established quantitative methods. Yet, quantitative methods could facilitate the evaluation and analysis process. Besides, experts also pointed out the need for long-term studies to assess the traces' effect over time or established material-driven design approaches for creating urban interfaces. Lastly, traces expert 1 emphasized the challenges with digital traces that *"...are not always very clearly reflected back to the person creating them"* and the need to research giving back ownership.

4.2.4 Results & Discussion: FRAMEWORK. Overall, this theme comprises three sub-themes, *Conceptual Construct*, *Extension*, and *Application*. The latter includes one sub-sub-theme, *Place*.

Conceptual Construct. All experts confirmed the relevance of the framework's dimensions and relationships. They also emphasized the importance of the material-place relationship for the urban outdoors that reveals where and how many people did what activity. All agreed it was a valuable addition to the original materials experience framework.

Extension. Suggested extensions and changes concerned the renaming of the *collaborate* relationship to increase understanding and to add *Time* as an additional dimension. Furthermore, they reflected on the role of agents and the displayed content, e.g., text information. However, they also recommended considering these in a second iteration and evaluating the updated version, as presented in this work, first.

Application. The experts saw the framework's benefit to systematically support before, during, and after the design process to evaluate whether all relevant influences had been considered and what effects may be expected when changing something in one dimension. On the one hand, this would support the creation process of interfaces and, on the other, visualize what influences the meaning of each dimension. However, they also expressed the need for some flexibility: *"If you're talking about the framework, I would say that they [the dimensions] are all equally important because that would accommodate, uh, sufficiently different design scopes [...] but within a particular design scope you may have some of those elements be more predominant than others at different times"*, UIxD expert 1. The length of the relationship lines could therefore reflect the different dependencies and hierarchies. *Place* was a newly added dimension and was discussed in more depth than the other dimensions. To create interfaces with the concept, experts thought it highly relevant to define the spatial context and the meaning of the place. This includes the identification of ongoing activities onsite, the place's spatial affordance, and non-physical aspects (e.g., data) that would influence its appearance and effect.

4.2.5 Summary of Step III. Altogether, the interview results validate the framework for physical contexts and confirm the *Traces in Use* as a design concept to create meaningful, social, and cultural user experiences for the individual and shared contexts. The results further emphasize the framework's usefulness and sensible overview of the relevant relationships and dimensions that are necessary to consider when applying the concept in a design process. We extended the framework about the temporal dimension that is valuable to account for changes over time; for example, to consider the shorter lifespan of digital technologies in contrast to the long lifetime of physically built environments. Given the framework's theoretical grounding and perspective, experts also mentioned that it would require its practical application in an actual design process to a) validate the dimensions and relationships and b) investigate which methods and tools to complement it. They imagined using it as a tool guiding in considering and accounting for all potential influences deriving from the dimensions and relationships on users' sense-and meaning-making of their interface designs. They also agreed on the equal importance of each dimension but emphasized that this might shift depending on the situation and project. Considering all input, we iterated on the framework resulting in the version presented in Figure 4 to create interface designs with the *Traces in Use* concept.

5 PROTOTYPING TRACES IN USE FOR INTERFACES: PROCESS AND MAKING [STEP IV A]

In the last Step (IV) of our work, we validated the *Traces in Use* concept practically in a design project to contextualize three urban interfaces. Additionally, we evaluated the framework by applying it throughout the design process for interface creation and testing. To assure greater generalizability of our results, we tested the interfaces at two different locations (see Figure 8). In contrast to the previous Steps, we formulated the following research questions to provide a clearer structure to this extensive last step of our work:

- **RQ1** How can we design and prototype a trace's appearance to contextualize urban interfaces? How can the *Traces in Use* framework guide and facilitate the design of interfaces incorporating traces?
- **RQ2** To what extent can urban interfaces that incorporate the *Traces in Use* design concept comply with heterogeneous user groups' needs and support a meaningful interaction experience?

To address these research questions, we followed *research in and through design* as the overarching approach [16]. Dalsgaard [16] propose this approach for conducting interaction design research in which the study of the design process is of relevance (research *in* design); at the same time, the researcher itself is involved in the experimental design project that is also leading to new domain knowledge (research *through* design). In regards to our research questions, we followed research *in* design to evaluate how the Urban IxD design process can be extended through materials experience design research and our *Traces in Use* framework more specifically; and research *through* design by employing methods from design practice (e.g., development of design concepts, prototypes) to gain insights into the contextualization of urban interfaces through the design concept.

To define the meanings and relationships of the different dimensions of our framework, we incorporated the meanings of place framework by Gustafson [37]. We analyzed and identified context-dependent design requirements and the places' meaning for two places of different architectural styles and meanings in the inner city of Munich, Germany, the Historical Square and the Community Area to inform the *Traces in Use* framework dimensions and their relationships (Step III). Furthermore, we introduced design considerations that guided our prototyping process to create the natural traces of use appearance recommended for outdoor places in subsection 3.2. Subsequently, we applied the material driven design (MDD) by Karana et al. [57] for the material and prototyping exploration. Figure 5 presents an overview of the iterative approach and applied methods. In the MDD and prototyping steps, the framework guided the collection and analysis of information.

During the design process, we used different media and tools commonly used for RtD documentation [5], such as photographs, sketches, and textual annotations. For understandability purposes, we present locations, design considerations, and the resulting interfaces (see Figure 8) in the form of an annotated portfolio [31], aiming to surface similarities and differences across the interfaces and the locations that the interfaces were designed for. Since the authors of this paper are distributed across the globe, the annotated portfolio was created collaboratively through the online whiteboard platform Miro[2]. The platform enabled to (re-)arrange and select the pictures, comment and highlight certain objects or materials, and visualize connections from the picture collection to the contextualization perspectives by Vande Moere and Wouters [103] and the *Traces in Use* framework. For locations (see Figure 6) and design considerations (see Figure 7), the annotation strategy was strongly guided by the particular method or approach that was followed in each particular design phase.

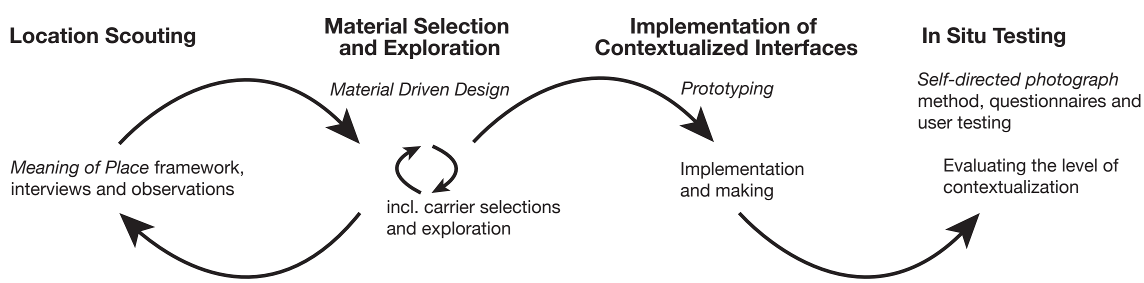


Fig. 5. The prototyping and in situ testing approach: We first scouted locations and analyzed them with the meanings of place framework. The results influenced the material selections and explorations in the following step and the carrier selection. Combining all interim findings, we then conceptualized and implemented three prototypes that we then tested in situ. The framework guided our design process and supported double-checking our interfaces.

5.1 Methods

The *meanings of place* framework [37] helps to analyze a place's meaning by considering three aspects, namely the *"self"* (the individual user-place relationship), the *"environment"* (physical features and events) and *"others"* (social norms and

[2]https://miro.com/, last accessed: December 2022

type of community). Through these three aspects, the method allows identifying design aspects and characteristics relevant to define the *People*, *Place*, *Material*, and *Practice* dimensions through field observations and interviews. The three cornerstones are influenced by and shape traditions, the place's organizations, and user associations. The material-driven design method [57] fosters material exploration and usage while aiming for meaningful user experiences. It includes four subsequent steps: i) understanding the material, ii) creating a vision for the materials experience, iii) integrating the materials experience characteristics, and iv) designing the concept.

5.2 Location Analysis and Characterization

To approach all cornerstones of the *meanings of place* framework [37], we conducted five interviews per site with urban dwellers about their reasons for visiting and connection to the places. Two authors conducted the place analyses, one moderating the interviews and the other taking notes. Additionally, both authors conducted field observations and desk research (e.g., reviewing newspaper articles about the places' events, history, etc.). Below, we present the results for the two selected locations by further linking them to the *Traces in Use* framework dimensions. It should be noted that we do not provide further details about the analysis process as the location analysis served as a preparation step only and is not the primary focus of this work.

Fig. 6. The two selected locations, the Historical Square (left) and the Community Area (right), with annotations based on the "meanings of place" framework [37] (in green: meaning of self, environment, and others) illustrating our location analysis and characterization process. Textual annotations relating to specific elements identified onsite are encoded through white background color; annotations of black background indicate the identified activities and intentions to visit.

We decided on two locations (see Figure 6): the Historical Square for its historical meaning, architecture, and atmosphere, and the second as a contrast to the first location, the Community Area, for representing a modern community area. At both places, we considered the location's spatial arrangements, materials, and surrounding objects to inform the design of our interfaces [111]. For example, concrete and stone were identified as predominant *Materials* at the locations.

5.2.1 Historical Square. The Historical Square is part of the city's first official residence from the 13th century and is known and valued by visitors (i.e., *People*) for its historical significance. In the past, lion cages and other animals were kept in the square, and today, lion statues are spread around the larger city area reminding visitors of their historical presence (*Material* dimension). The location features a wide-open space with the main road leading through it and a fountain in the middle (*Place*). It is located next to the city's inner shopping mile and serves as a spot for people to escape the crowds. As such, it is often used to enjoy a lunch break or relax (*Practices*), which is also why the location is described as a calm oasis in a historical setting.

5.2.2 Community Area. The Community Area is a relatively new complex with office buildings, hotels, stores, restaurants, and a small container village. The place was a former factory, albeit with very few reminders of its past. In its more recent history, the place was known for its vibrant nightlife and music scene, with bars and clubs located around the area. Today, the container collective offers community activities such as gardening or smaller performance areas for musicians (i.e., *Practices*). In particular, the container collective still features a lot of graffiti on the walls (i.e., *Material*). Various people go about their daily business here: workers (i.e., *People*) taking their lunch break, people taking a walk, going shopping, etc. As such, the location's meaning for individuals is that it is a place to relax, socialize or connect with the local community (i.e., *Place*).

5.3 Design Considerations

We focused on natural material traces that trigger the impression that many users repeatedly used the interface over time to generate shared, common understandings and associations. These considerations link to, for example, the positively associated patina effect (see Table 1, Step I & II) and understanding of such traces about other people's activities at shared places (Step III). In addition, we aimed to reflect on the situation in the target environments and increase the social connectedness when sensing and perceiving the traces in context. The *Traces in Use* framework supported the design process by setting the gathered information in relation and identifying traces that represent the connection between the different dimensions. To create the time-dependent causation effect, we took the example of rubbed-off parts of a statue[3] or a shortcut caused by users cutting the corner of a street[4]. In such cases, the material interaction results in *irreversible, intensifying changes* that may lead to material dissolution overall [6, 99]. Additionally, we applied slightly irregular shapes and surface texture transitions to arrive at a natural trace appearance, which encourages exploration and increases interface embeddedness as identified in section 3. We also considered the seven material characteristics that influence the traces' affordance and recognizability: differences in color and texture, distinction, cultural context, patina, physical familiarity, and depth.

5.4 Designing the Interfaces: MDD and Prototyping

Following the MDD method [57], we selected materials and objects identified from our place analysis and interlinked the materials' and places' characteristics. Next, we explored different ways of creating material patterns shaping traces of use following our design considerations as presented above. Lastly, we applied the traces onto the objects turning the object from carriers into interfaces. We decided to create three interfaces in total (see Figure 7): for the Historical Square, we designed the Lion interface, a metal-like lion statue with integrated traces of manually rubbed nose and leg. If generating heat through the touch interaction at the indicated areas, the material changes its color, and a hand-written message underneath becomes visible. We also designed a Drum interface for the Community Area incorporating multiple, overlapping hand-prints that, when touched/beaten, produces sounds to create the impression of playing with

[3]http://www.the-culture-counter.com/juliets-right-breast-and-other-lucky-body-parts/, last accessed Dec. 14th, 2021
[4]https://cxeye.wordpress.com/2015/10/07/design-vs-ux-vs-cx/, last accessed Dec. 14th, 2021

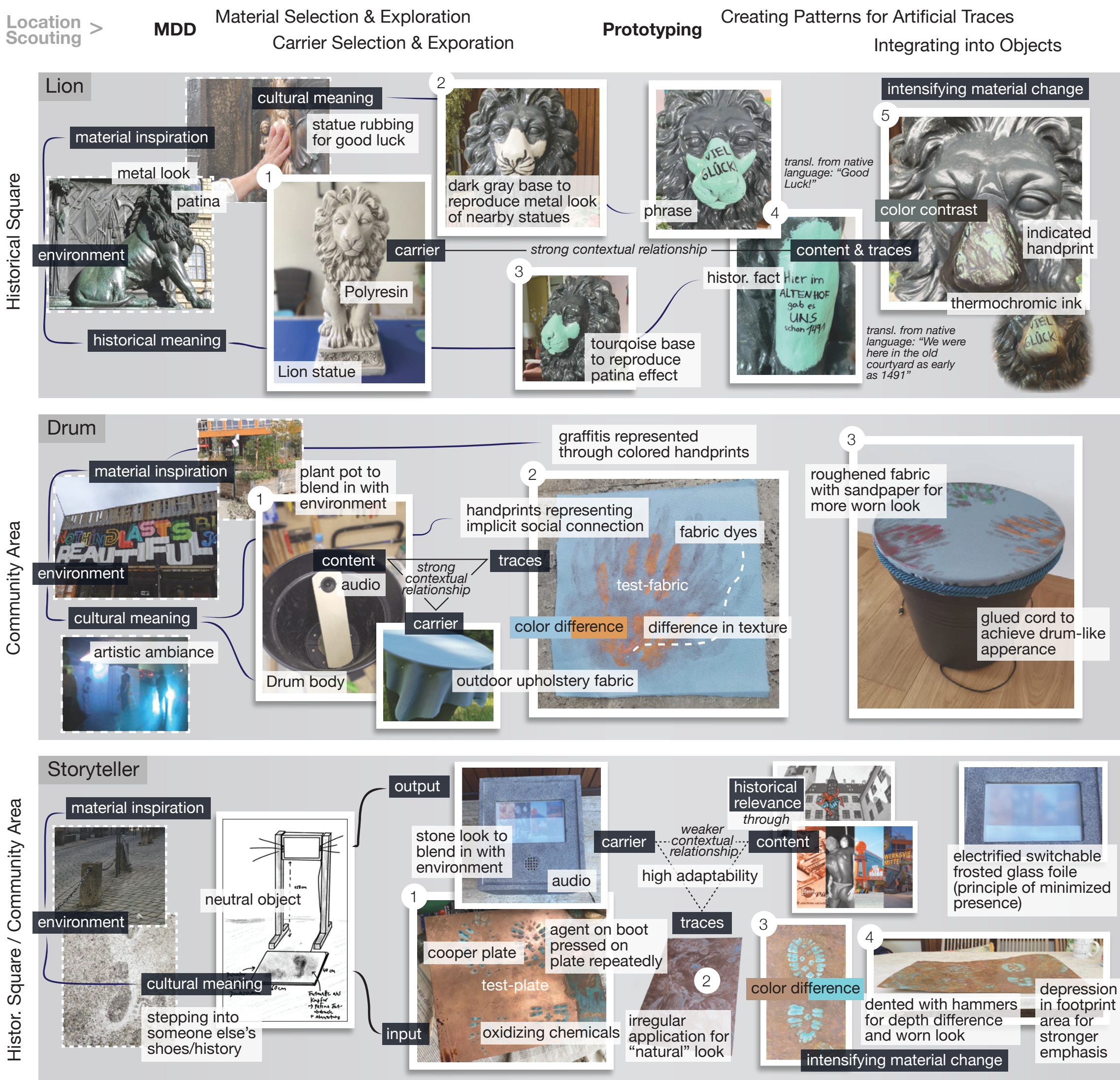


Fig. 7. Annotated portfolio illustrating the *research in* and *through design* approach for each interface, including inspirations from the location analysis, mapped onto the four contextualization perspectives (the three original: Environment, carrier, content, and one new perspective, "material" as presented in Figure 13) in the MDD method, and manifested in the finalized interfaces. Textual annotations relating to specific design characteristics and choices pertaining to the interfaces are encoded through white background color; annotations of black background color indicate the conceptual implications of designing *Traces in Use* interfaces.

someone or something. Lastly, we created a more 'contextually-neutral' Storyteller interface with an input and output component. The Storyteller's input is a copper plate with artificially created foot imprints. When triggered, the output component changes visibility showing images about the location and playing short audio content. The Storyteller has been designed for both locations, and the content has been adapted accordingly. We used the *Traces in Use* framework for double-checking each interface's composition and their relation to the identified place meanings.

5.4.1 Lion Interface. The Lion statue directly connects to the place's former function as a lion enclosure and today's local custom to rub lion statues' noses for good luck. We explored color and texture differences for the traces of use, working with different varnishes and thermochromic ink. To indicate the interactive areas through a patina effect [44], we painted those parts with a turquoise base. The rest of the statue was painted in black to achieve a color contrast [44] and to mimic the metal look of actual statues. To complete the impression of age and long-term usage, we applied the traces by wiping over the still-wet thermochromic ink shaping them similarly to a multitude of hand-prints on top of each other. Underneath the ink, we wrote two hand-written messages related to the cultural and historical meaning of the object and place. The interface complies with the concept of 'embeddedness' [53] through its physical shape and material and its historical and cultural notion. We located the interface along the main walking path facing towards the square so that it was additionally spatio-contextually embedded (see Figure 8, left).

5.4.2 Drum Interface. The Drum interface metaphorically embodies the artistic ambiance of the Community Area, including the busy social life, manifested through the multitude of hand-prints. Users are supposed to feel connected with others by touching the hand-prints and being reminded of the location's fun and creative nightlife. We created the Drum using a plant pot and a polyester cloth that we processed with sandpaper and coarse files to increase the overall weathered appearance. The traces reflect in three different colored hand-prints in combination with overlapping brown hand-prints on the drum's batter head. The color also changed the fabric's texture, making the difference visible and tangible. The depth difference became more significant the thicker we applied the colors. The hand-prints represented the colorful graffiti that adorned the place's walls now and then. The interface was positioned in plant boxes along the location's main path (see Figure 8, right) and close to a music bar so that it was located within the area where people come to socialize. We embedded the Drum interface culturally, physically, and spatio-contextually.

5.4.3 Storyteller Interface. The Storyteller, with its footplate, metaphorically corresponds to the meaning of 'stepping into someone's shoes and, thus, someone's history. The output, a print containing pictures, was integrated into a box with a stone-like look and located behind a frosted glass screen[5]. The frosted glass became transparent when connected to power and was electronically connected to pressure sensors that we integrated into the footplate. The traces were placed on the pressure plate's copper sheet to indicate where users should step. They consisted of patina footprints created with oxidation agents. Additionally, we used the agents to age the rest of the plate artificially. Finally, we used hammers to dent the surface and create a depression at the footprint to emphasize the traces further. For the Community Area, we placed the output box in one of the wooden plant boxes and at the Historical Square, on top of one of the stone pillars in the middle of the square (see Figure 8, center). The footplate was placed underneath. When choosing the placement, we ensured that the areas described in the audio-visual story were within sight. The Storyteller was, thus, spatio-contextually and historically embedded, but its physical shape did not relate to the respective locations.

6 FIELD STUDIES: INTERFACES, CONCEPT AND FRAMEWORK EVALUATION [STEP IV B]

Our project additionally comprised two mix-method field studies to test the level of contextualization of the three prototypes with a total of N=40 participants, 20 at each location. We conducted both studies over three weeks. Each session took 25-45 minutes, depending on participants' thoroughness in exploring the locations.

[5] https://www.system24.de/shop/schaltbare-folie-and-zubehoer/musterfolie-gerahmt/, last accessed December 28th, 2021.

Fig. 8. The three prototypes of contextualized interfaces that we deployed at two different locations (from left to right): the Lion statue and the Storyteller deployed at a Historical Square, and the Storyteller and the Drum deployed at a Community Area.

6.1 Participants

Participants were recruited via the university's networks and social media accounts. All gave informed consent according to general data protection regulations (GDPR) and followed the local hygiene and social distancing rules[6]. 20 participants identified themselves as female (eight at Community Area and 12 at Historical Square), 20 as male (12 at Community Area and eight at Historical Square). More than half of the participants (n=23) had not been at the respective place within the last year (10 at Historical Square; 13 at Community Area). In addition, 12 participants had been there once or twice (seven at Historical Square; five at Community Area), three between three to five times at the Historical Square, and two had visited the Community Area more than five times.

6.2 Methods

We applied the self-directed photograph method [78], ensued by a questionnaire (Questionnaire I). By this, we followed the approach by Hirsch et al. [46] to assess the traces' potential in supporting the design for heterogeneous user group needs and interests by evaluating how much the interfaces would catch participants' attention (RQ2). Furthermore, this study allowed us to assess how well the interfaces were embedded into the surrounding in relation to their recognizability. Afterward, we did user testing with the interfaces, followed by a questionnaire (Questionnaire II) to assess users' sense-and meaning-making of each interface in relation to their surroundings and other users.

Self-Directed Photograph Method and Questionnaire I. In the self-directed photograph method, participants took pictures of the place and objects they perceived as relevant to the task at hand according to their profile. The *persona profiles* included an event manager and a lunch break taker profile (see Table 2). The first profile corresponds to non-users [97] who would not be interested to learn more about the surroundings and represented the test group. The second profile complies with users interested in the environment and functioned as the control group, which was supposed to notice the interfaces. Both profiles related to observed user profiles at both locations and allowed us to compare the need of heterogeneous user groups.

Similarly to Hirsch et al. [46], we extended this method with an additional questionnaire to evaluate the interfaces' obtrusiveness and embeddedness, thus aiming to answer our second research question (RQ2). The questionnaire, filled out for each interface, comprised a 7-point Likert scale (1:very low to 7:very high) regarding the following six attributes:

[6]The study took place during an ongoing pandemic requiring reduced social contacts and disinfection of all tools after each run.

embeddedness, cultural suitability, perceptibility as an interface, perceptibility in the environment, recognizability, and easiness-to-ignore. The questionnaire also included open-ended questions to understand the reasoning behind each rating, for example, reasons for or against considering the interfaces. We also asked participants whether they had noticed them when they had not photographed the interfaces.

User Testing and Questionnaire II. In the second study, we conducted a user test asking participants to interact with the interfaces and rate their' usability, perception, and interpretation. For this, we prepared a questionnaire including usability rating questions adopting similar attributes to those of the attrakDiff [39], such as how useless or useful, unaesthetic or aesthetic, conventional or novel, confusing or obvious, complicated or simple, bothersome or pleasing and boring or interesting, each interface was to participants. We also included the usability test to validate whether participants experienced any issues that might influence the interfaces' contextualization and to challenge the design concept for potential gaps or limitations. Additionally, we added open-ended questions about whether the traces facilitated how the participants construed and understood the relationship between the interfaces, the place, other users, and themselves. Lastly, we asked participants to rate the trace designs as alternative control elements and their interaction experience. During this study part, we took notes and observed participants' interactions with the interfaces.

Table 2. The two user profiles and tasks applied in the study [46].

	Abbrv.	User Profile	Task
Control Group	A	Lunch break taker	Take pictures of everything where you could get further information about the location or information interfaces as a frequent visitor whose main intention is to relax and take your mind off of work.
Test Group	B	Event manager	Take pictures of everything that could help you to decide on the place as an event location.

6.3 Study Procedure

We introduced participants to their profiles for the self-directed photograph study at each location, followed by the first questionnaire. Afterward, we asked them to interact with each interface and fill out the second questionnaire. For the user testing, we guided all participants to the interfaces. We observed how they approached the interaction, what gestures or interaction types they tried, what functionalities they expected, and why. We intervened if participants took longer than 2 minutes to understand the interaction.

6.4 Data Analysis

Our analysis included four steps per place using descriptive and inferential statistics and thematic coding: First, we related the results from the self-directed photograph study with the ratings from the first questionnaire to determine whether the interfaces could balance the requirements of heterogeneous user groups. We reviewed participants' qualitative feedback, looking for data points (quotes) to identify reasons for noticing or considering the interfaces as task-relevant. Second, we considered the ratings about how suitable and embedded the interfaces were perceived per environment. This step evaluated whether users could connect them to the local identity and their level of embeddedness into the built environment, both relevant aspects to contextualize interfaces [103]. For the attribute correlation, we used the Shaprio-Wilk-Test, showing that the data was not normally distributed. We applied the Kendall's rank correlation coefficient in R version 1.2.5033, including the packages "corrplot", "ggpubr", and "psych". Extending these results, we thirdly evaluated the ratings about the traces' usefulness and participants' comments to assess how much the interfaces promoted engagement [103]. Fourth, we looked into the ratings about the traces' overall understandability in addition to the participants' perceptions and assumptions about their making and their connection to the place and other users. This step aimed to evaluate the design strategy's effect on fostering sense-making [53] and the user-place relationship [42]. To evaluate the Likert-scale data of points three and four, we used the "Likert" package in R and coded the responses thematically by familiarizing ourselves with the data and clustering them into thematic groups [8].

6.5 Results Historical Square

Table 3. Recognition frequency of the interfaces per group (each $n = 10$) and place, including the mean in % and standard deviation.

Group	**Photographed**				**Noticed**			
Historical Square	Lion	Storyteller	*M* in %	*SD*	Lion	Storyteller	*M* in %	*SD*
Control Group	7	8	75%	0.7	9	9	90%	0
Test Group	2	0	10%	1.4	5	5	50%	0
Community Area	Drum	Storyteller	*M* in %	*SD*	Drum	Storyteller	*M* in %	*SD*
Control Group	4	3	35%	0.7	6	6	60%	0
Test Group	0	0	0%	0	3	4	35%	0.7

6.5.1 Self-Reported Photograph Study and Questionnaire I: The Interfaces Are Recognizable and Non-disruptive. The results indicate that our interfaces were physically and spatially well-embedded to be recognizable for interested users yet non-disruptive for non-users. For test group B, five participants noticed both interfaces (see Table 3). However, only two from this group photographed the Lion, considering it task-relevant, and none perceived the Storyteller as relevant. In comparison, for control group A (lunch breaker profile), nine out of ten participants noticed both interfaces, of which seven took photographs of the Lion and eight of the Storyteller. Seven participants from group A considered the Lion interface task-relevant because they either already knew the historical connection, thought it suitable for the environment, or noticed the color difference indicating the traces and that others had touched it before. In contrast, participants from group B mentioned that the Lion interface was hard to see with its dark colors in the shade, which is why they did not bother further. For example, P28 (B) stated: *"It blends in very well with the environment. As an event planner, I consider it attractive, but not relevant to the decision as to whether the location is suitable for an event"*. Similarly, participants from group B mainly overlooked the Storyteller because of its stone finish or because it would not be task-relevant. However, participants from group A stated that it caught their attention because it was positioned in the middle of the square (n=5), would look like an info-point (n=2), or they perceived the footplate as striking (n=1). These statements align with the ratings presented in Figure 9 showing that both interfaces were rated very high for suitability and embeddedness into the environment, and high for perceivable as interfaces but also high for easy-to-ignore. Yet, the correlation tests showed no significant difference in the ratings between the groups for either of the interfaces. While the Storyteller's recognizability was also rated very high, the Lion was only rated moderately, considering the dark color choices that made it partly hard for participants to distinguish it in the shade. Lastly, both interfaces were rated moderately perceivable in the environment.

6.5.2 User Testing: The Traces Provided an Easy-to-Understand Affordance but Triggered Different Aesthetic Perceptions. Participants rated the interaction with the Storyteller higher than with the Lion across all questionnaire items, as shown in Figure 10. Both were rated as very simple (Lion M=6.35, SD=1.5; Storyteller: M=6.85, SD=0.37), and useful (Lion: M=6, SD=1.5; Storyteller: M=6.75, SD=0.44). The Storyteller was further rated very obvious, pleasing, and aesthetic, whereas

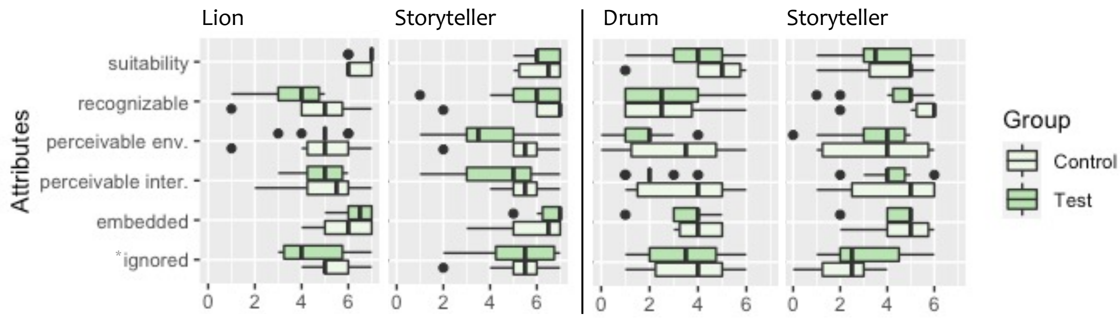


Fig. 9. Ratings for the Lion and the Storyteller at the Historical Square, and the Drum and Storyteller at the Community Area regarding the six attributes asked in the first questionnaire. The attributes perceivable in the environment is here abbreviated as perceivable env., the perceivable as interfaces as perceivable inter., and the attribute easy-to-ignore with *ignored.

the Lion was rated obvious, pleasing, but only rather aesthetic. Both interfaces were rated as moderately interesting and novel. Based on our observations, the interaction seemed easy to understand: 17 participants rubbed the Lion's marked spots as intended without further instructions, whereas three participants only slightly touched the spots and needed additional aid. For the Storyteller, 19 participants stepped immediately with both feet on the plate, whereas one stepped more carefully with one foot first. None needed further instructions. Only two participants tried to interact with the display during the interaction, similar to a touch screen.

14 participants related the perception of the traces for both interfaces to prior interactions and interpreted them as markings to support intuitive handling. However, participants interpreted the traces' deeper meaning differently for the two interfaces. For the Storyteller, three participants knew the concept from other installations, drawing a direct relation to the content and the context: *[There are] other devices that work similarly. "Follow in the footsteps of your ancestors."*, P21 (A) or *"Perhaps the court staff was already standing here[...].",* P28 (B). In contrast, the Lion interface triggered even higher cultural and historical sense-making by participants (n=7) relating it to the local custom of rubbing a lion for good luck, as intended by design. Due to its worn look, three people felt slightly uncomfortable touching the statue (which they still did voluntarily). Another three emphasized its suitability and good design.

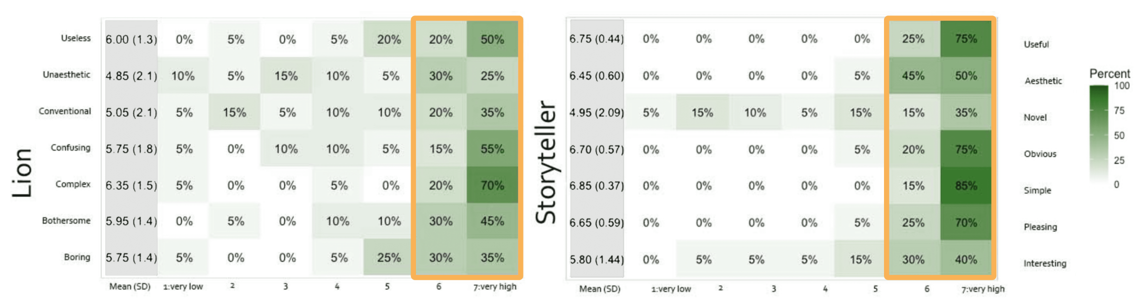


Fig. 10. Ratings per interface: left the Lion's usability, right, the Storyteller's. Both interfaces confirm a good to a very good usability.

6.6 Results Community Area

6.6.1 Self-Reported Photograph Study and Questionnaire: The Interfaces Were Harder to Recognize within the Environment. At the Community Area, results from the self-reported photography showed differences between the groups (see Table 3). Yet, the interfaces were too unobtrusive overall. Four participants from group B noticed the Storyteller and three the Drum, but none thought them task-relevant. In comparison, six participants from group A noticed the interfaces, four thought the Drum, and three the Storyteller task-relevant. Participants explained the low detection rate by having either focused their attention in another direction or did not recognize the interfaces, particularly the Drum: *"I paid attention to activity offers or signposts."* P2 (A) or *"It stood quite inconspicuously on the side in the flower pot. I've oriented myself in the other direction."* P18 (B). The ratings presented in Figure 9 support the statements showing that the Drum was only a little recognizable in comparison to the Storyteller and that it was also relatively imperceptible as an interface or in the environment. Nonetheless, four participants from group A photographed the Drum, and three photographed the Storyteller (see Table 3). The table further shows that more than double the participants noticed the interfaces but did not think them task-relevant. While this was the goal for our test group, it also shows that both interfaces were too unobtrusively designed and positioned, and not meeting participants' expectations of what to look for. The correlation tests showed no significant differences either.

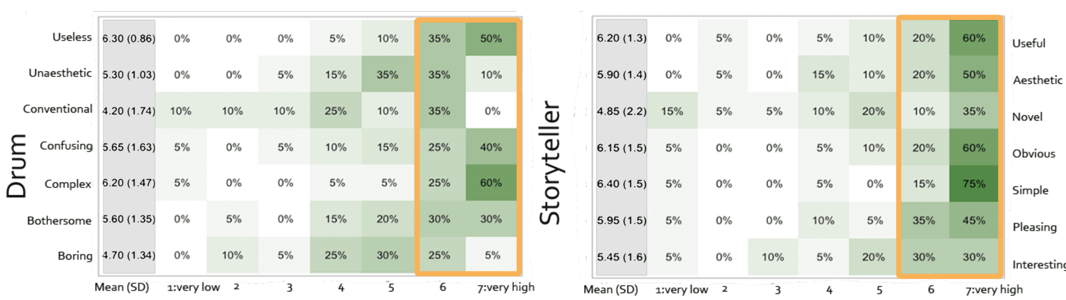
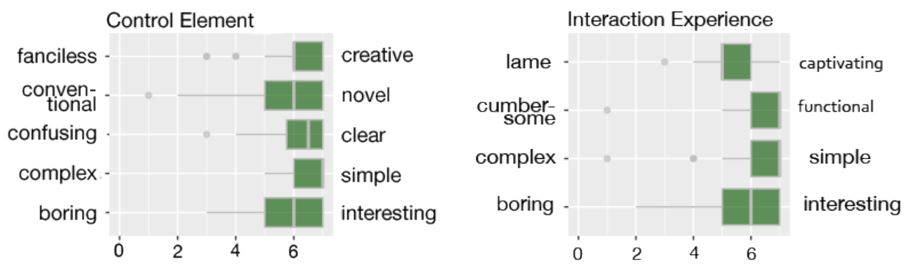


Fig. 11. Ratings per interface: left the Drum's usability, right, the Storyteller's. The Storyteller received higher usability ratings overall.

6.6.2 User Testing: The Trace Design Was Easy to Understand and Interfaces Were Perceived Useful. Figure 11 shows that both interfaces were found to be simple (Drum: M=6.2, SD=1.47; Storyteller: M=6.4, SD=1.5) and useful (Drum: M=6.3, SD=0.86; Storyteller: M=6.2, SD=1.3). Additionally, their handling was evident to participants, and their design was pleasing and rather aesthetic. However, participants found the designs only slightly novel and interesting. Our observations further support that both interfaces were easy to understand: for the Drum, eight participants immediately understood how to interact with it, ten explored it for a couple of hand beats before learning how to use it, and the remaining two needed instructions. In comparison, all but one participant (n=19) directly stepped onto the Storyteller's plate and, thus, activated the content display. However, ten participants also tried interacting with the output screen via touch, not perceiving its intended inactivity. For the open-ended questions about the traces and how they relate to the content, participants (n=11) drew connections to former users. Two also stated that the traces could be a message to the next person about how to use the interfaces, particularly for the Drum. The Storyteller footprint triggered three participants to think of former workers and a construction site, thus associating the displayed content with the former factory and the architectural place changes between now and then.



(a) (b)

Fig. 12. Overall ratings about the *Traces in Use* designs to indicate control elements and the interaction experience.

6.6.3 Ratings Considering the Traces in Use. Altogether, the traces were rated as very creative, clear, and simple alternative control elements. Moreover, as shown in Figure 12, they were also rated as novel and interesting. Besides, participants rated the experience of interacting with the traces as very simple, functional, and rather captivating and interesting. Four participants further reasoned the high ratings by referring to the traces' simplicity and stated the traces intuitively indicate the interfaces' affordances. Overall, participants reported their interaction experience as fun and would like to extend the interfaces' functionalities.

6.7 Discussion STEP IV

Before entering this work's overall discussion, we shortly reflect on the meaning of our findings and our approach for the design concept and the framework considering this section's research questions.

6.7.1 Applying the Traces in Use Design Concept & Framework. We explored the *Traces in Use* design concept by applying the framework and the findings from Steps I and II in the design process of creating three contextualized urban interfaces. Regarding **RQ1**, the theoretical framework helped us to identify appropriate methods and analytical tools for the different design phases, such as the meaning of place framework [37] for the location analysis, and the MDD method [57] for designing and prototyping the traces. It further scoped the analysis to define the dimension and their relationships for each place. Before beginning any design work, we analyzed each place regarding its social, historical, and cultural meaning. This includes the analysis of the places' role and meaning for inhabitants and urban dwellers (*People* dimension), how and for what activities the places are used (*Practice* dimension). Furthermore, the analysis allowed us to identify place-specific characteristics, for example, the artistic atmosphere and colorful walls at the Community Area. Such characteristics influence the choice and meaning of traces so that they reflect the local community [102] and are relevant to individual users [82]. Additionally, we inspected materials and objects onsite (*Material* dimension), which influenced the material selection for our follow-up process. Consolidating the findings for the dimensions *People*, *Practices*, and *Materials*, resulted in an understanding of the *Place* dimension, allowing us to define the meanings of each place. Consequently, considering the framework under applying the meaning of place framework and the MDD supports in defining context-specific design requirements for creating contextualized *Traces in Use* urban interfaces.

6.7.2 Reflecting on the Level of Interface Contextualization. According to Vande Moere and Wouters [103]'s model, urban interfaces can be contextualized by considering three perspectives: content, carrier, and environment. To analyze the level of contextualization of our *Traces in Use* interfaces, we build on the model by identifying four contextualization perspectives for the Drum and the Lion interfaces: the content, material, carrier, and environment perspectives, and three perspectives for the Storyteller: content, material, and environment. We added the material perspective as a contextualization layer for *Traces in Use* interfaces because the meaning of the trace and the meaning of the carrier are interdependent but incorporate meaning on their own. Thus, they should be considered independently. We exemplary visualize the different perspectives along the example of the Lion interface in Figure 13. Setting these contextualization perspectives in relation to our framework, we see complementary effects on both sides. Vande Moere and Wouters [103]'s model lacks design dimensions considering traces, material, time, and people. In contrast, our framework excludes a content dimension and consolidates both carrier and materials under the *Material* dimension. As the *Traces in Use* framework serves the purpose of setting the design dimensions in relation to the meaning of traces, the traces are detached from the content and integral parts of materials and objects. Consequently, we keep the *Traces in Use* framework as-is. But we see value in adding a material layer to the contextualization perspectives to emphasize the meaning of traces and other material characteristics dissociated from the carrier perspective. These findings emphasize the framework's value when applying the *Traces in Use* concept as it highlights the different levels of detail that need to be considered in the design of contextualized interfaces.

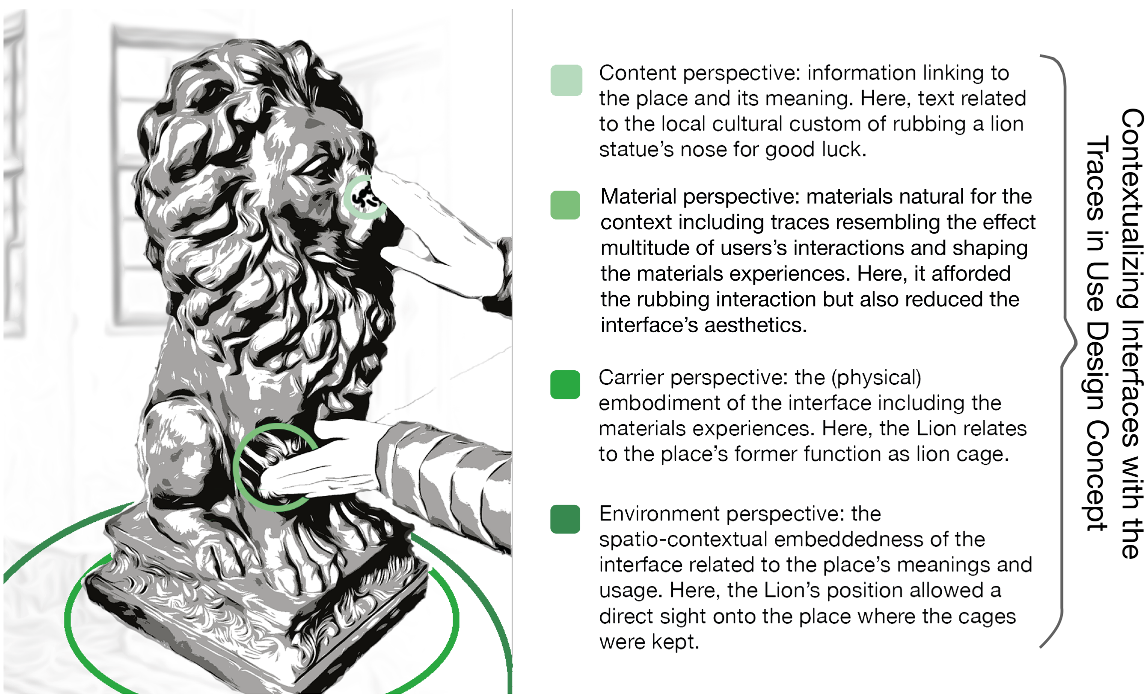


Fig. 13. Designing contextualized interfaces using the *Traces in Use* requires considering four perspectives, here presented along the example of our Lion interface: 1) content, 2) material, 3) carrier, and 4) environment.

6.7.3 Heterogeneous User Group Needs and Meaningful Interaction Experiences. Responding to **RQ2**, our results showed that our interfaces could support heterogeneous user group needs regarding the balance between being well embedded and unobtrusive, yet explicit enough and recognizable. This accounts particularly for both interfaces at the Historical Square. At the Community Area, participants from both groups either failed to notice the interfaces or did not find them task-relevant due to them being too unobtrusive or ambiguous. This shows that the type of carrier and their positioning within the environment influence the interfaces' understanding and meaning. Counteracting these issues, we could imagine finding potential solutions in combining the *Traces in Use* with findings from prior work, such as applying ephemeral and dynamically changing traces (e.g., Hoggenmueller et al. [49]), or integrating features from high-resolution displays (i.e., Wiethoff and Hoggenmueller [107]) into the carrier for attention guidance. Nonetheless, our interfaces supported the design for heterogeneous groups considering the group results (see Table 3).

Regarding the meaningful interaction experience, we consider our results from the self-reported photography questionnaire, confirming the interfaces' suitability and embeddedness across conditions. The traces supported our interfaces' physical, spatial, and cultural embedding, which fosters users' sense-making [53]. There is, however, a solid physical and metaphorical interconnection of traces and carriers which might have influenced the results, making it unclear how much the traces alone contributed. Nonetheless, the lion interfaces, combined with the traces, allowed participants with the appropriate pre-knowledge to relate to the local cultural custom of rubbing the statue's nose for good luck. This further emphasizes the relevance of the dimensions *Behavioral Settings* in our framework, which comprises cultural norms and behaviors. Similarly, the Storyteller concept of stepping into someone else's shoes supported participants in connecting to the place's historical significance and thinking about former users' behavior. Thus, material traces can support interface contextualization while keeping them unobtrusive for non-interested users.

6.8 Summary Step IV a+b

Overall, the field study, including the design process, introduces how the *Traces in Use* design concept can be practically applied. The qualitative user feedback confirmed the traces effect of increasing users' sense- and meaning-making. Results from the self-reported photography method revealed that interface contextualization is essentially influenced by the interface positioning in the environment and the carrier choice. Regarding the making of the interfaces, the *meanings of place* framework [37] supported the identification of onsite conditions and potential design features. Complementary to this, the material-driven design method [57] supported the material exploration and implementation in the follow-up step of creating the interfaces. Combining both methods allowed us to integrate socio-cultural meanings into the interfaces through the traces by taking advantage of the individual, material characteristics. The *Traces in Use* framework further supported the process in both steps to set the gathered information in relation to each other and to identify traces and carriers that trigger sense- and meaning-making. We also introduced the material perspective as a new level of contextualization to Vande Moere and Wouters [103]'s model. This perspective emphasizes the role of materials and their characteristics in interface contextualization (see Figure 13). The field study results confirmed that our interfaces partly supported an unobtrusive yet recognizable embedding of interfaces into shared, public places. The crafted material traces triggered participants to think of other prior users and the surroundings, including the places' history or cultural meaning confirming the concept's potential for contextualizing interfaces.

7 DISCUSSION AND FUTURE WORK

Our work was motivated by the lack of design approaches supporting the contextualization of urban interfaces [103, 111]. Additionally, public urban interfaces have to comply with heterogeneous user group needs [27, 41, 46]. We approached these challenges by developing and evaluating the *Traces in Use* design concept. The concept reuses natural traces of use characteristics by exploiting their qualities of being recognizable and meaningful (Steps I + II) and adds an additional information layer to the interfaces. Hereafter, we will first reflect on our approach and then discuss the differences between our design concept *Traces in Use* versus natural traces of use. Based on that, we discuss our design concept *Traces in Use* first for the contextualization of urban interfaces to then reflect on it as a strong design concept, a form of intermediate-level knowledge in interaction design research [51]. We conclude with an interpretation of our results in relation to digital and virtual realities and a discussion of study limitations along with opportunities for future work.

7.1 Reflection on the Overall Approach

Steps I + II. We began this research by identifying and analyzing natural urban traces of use presented on photographs (Step I), followed by an initial material exploration of the making of trace designs in a lab study (Step II). Through this approach, we identified trace characteristics that should either be avoided or included in the design process. For example, traces that were considered rather difficult to perceive and interpret, such as scratches or noisy carriers as presented in Table 1, were excluded, whereas the patina effect, which embodies long-term and repeated usage, showed high appreciation in both steps (I + II). In Step II, we explored trace designs for concrete interfaces because it is a ubiquitous urban material. Concrete is also an unusual interface material, which partly influenced the participants' ratings and opinions to be either very curious about or opposed to it. Yet, that supported us in understanding the traces' potential to increase interface affordance and recognizability for touch interactions.

Alternative methods for Step I are collecting images through crowed-sourced image databases or exploring touch-related traces in the lab instead of looking into natural traces of use. However, the first would have required to control the content for misuse and quality, and the second would have produced types of traces and their characteristics that do not relate to urban environments. Similarly, co-design workshops enable exploration together with users, including the exploration of various material traces. Yet, that still requires a pre-selection of materials and providing participants with particular use case scenarios or contexts. As there is no prior work about the making of physical material traces to create interface control elements, we explored different making strategies focusing on one material first [45] instead of applying alternative methods in Step II. We further decided on this structured approach (Steps I + II) for the following reasons: by understanding what people already associate with natural traces of use, we took advantage of the structure-mapping [23, 71, 90] and integrated trace characteristics that trigger users' sense-and meaning-making. Building on the lessons learned from this pilot investigation, we later applied these strategies to make other material traces, and across three fully functional interface prototypes (Step IV).

Step III. Our initial explorations also revealed the need for tools and methods to create and evaluate contextualized *Traces in Use* interfaces. Hence, we developed the *Traces in Use* framework (Step III). This is meant as a design tool applied throughout the design process including the context analysis, ideation, design, and evaluation phases to iteratively develop and evaluate the prototypes up to the final interface. The framework supports defining and validating the interfaces against the design dimensions and relationships that may influence their contextualization and the interface design. We define it as a theoretical framework, which makes it applicable to other contexts and beyond the scope of the specific design artifacts presented in this article. We assessed our framework in expert interviews and a field study confirming its usefulness for physical environments. An alternative evaluation method provides a comparison to other previous frameworks and theories. Yet, our approach included experts with the theoretical know-how and the knowledge about current challenges and limitations when designing with traces or for urban environments. Our evaluation is also limited and will require the framework's application in future design projects for a full assessment. For example, the *Traces in Use* framework excludes non-human stakeholders such as animals or artificial agents such as robots. The latter are increasingly scattered around the city [69, 84] and, similar to animals [27, 100], influence people's interaction with the environment and leave their own traces [48]. Accordingly, we do not consider this framework all-embracing but a design tool that can be used to design for different application contexts, focusing on humans.

Step IV. We lastly evaluated the *Traces in Use* concept practically in Step IV (a+b), which confirmed the concept's potential to support the contextualization of urban interfaces [112] by being suitable for and well-embedding them into the environment and fostering users' sense- and meaning-making. The applied research in and through design approach [16] informed the making of the interfaces by steadily reflecting on the characteristics of natural traces and the creation of artificial context-specific ones. Following a design-led approach enabled us to gather insights about the socio-cultural condition and relationships in public, urban places that essentially influence the contextualization of interfaces. While the *Traces in Use* framework supports setting the gathered information in relation to each other, it required the meaning of place framework [37] to analyze relevant place characteristics. The framework originates from environmental psychology and ignores the role of technology in the people-place relationship. This requires designers to carefully deduct interaction and interface design-relevant characteristics based on the previously identified meanings of a place. Currently, there is no alternative HCI tool available. This emphasizes the need to develop design research tools and methods that support a tailored place analysis to design contextualized urban interfaces. Similarly, we applied the MDD method [57] to explore material changes and qualities that are linked to the respective place and allow for meaningful trace designs. Synthesizing the results from both methods, allowed us to define the interface contextualization concepts. Throughout our work, we identified synergies between materials experience design [33, 58, 59, 86], Urban IxD [29, 82, 103] and environmental psychology [37]. The variety of applied methods in Step IV reflects the complexity of designing contextualized interfaces that foster users' sense- and meaning-making. In our work, we combined methods and tools from different fields, revealing inter-dependencies between materials experience design, environmental psychology, and Urban IxD.

7.2 From *Traces of Use* to *Traces in Use*

We turned natural traces of use characteristics, such as the patina effect, into the *Traces in Use* design concept. With this, we aimed to define a design concept that supports interface contextualization to increase socio-cultural awareness and understandability [111]. In line with previous research (e.g., [56, 101]), the *Traces in Use* design concept should comprise trace characteristics that support sense-and meaning-making to deepen the socio-cultural connection to other users and their surroundings. Consequently, we evaluated and selected natural traces of use characteristics that can be elevated for the user experience and interface contextualization. Another difference between natural traces of use and the design concept is that the artificially created traces are an integral part of the interface design and purposefully embedded. Prior work has mainly looked into understanding traces of use as a result of actual user interaction (see, e.g., [40, 77]) with few exceptions that created artificial traces to mimic prior human interaction [88]. We consider both relevant for the *Traces in Use* design concept: on the one hand, the concept considers how to reveal and emphasize traces that naturally developed over time and use. On the other hand, the concept, as explored in this work, includes traces that are artificially created without originating from an actual interaction or relationship by making use of knowledge from materials experience design research. Since we focused on physical material traces, we explored materials and their characteristics to make them appear as if there was an interaction without waiting for the changes to occur naturally.

This distinguishes the concept from natural traces of use, as the design can partly influence and orchestrate timely development. Furthermore, users interacting with the traces of a *Traces in Use* interface trigger a reaction from the interface, such as activating the Storyteller's display or Lion's appearing text message. The concept incorporates traces as design features that connect the users with underlying functionalities and features. In comparison, natural traces of use do not provide access to further information or connections.

7.3 *Traces in Use* for Interface Contextualization in Public, Urban Places

Our work was guided by the question of how natural traces of use can be leveraged to contextualize urban interfaces. Synthesizing research findings across the different steps in our work, we present considerations and conclusions for designing with traces in public, urban places.

7.3.1 Public, Urban Places Change the Traces' Meaning Compared to Private Contexts. Previous work by Tsai et al. [98] and Dong et al. [20] explored traces to reflect individual users' intimate, personal meaning with their belongings and homes. In contrast, public, urban places are designed for shared, albeit less personal interactions, and require accommodating a wide range of user needs. In line with our expert interview results (Step III), this makes public, urban places a more complex and challenging context to design *Traces in Use* interfaces. Specifically, we identified four aspects that need to be considered when designing *Traces in Use* interfaces in shared public places: 1) in comparison to private contexts, the feeling of ownership for the object or the place changes and decreases in comparison to private contexts (as demonstrated in Step I); 2) there are multiple levels of meaning as seen, e.g., in the meaning of place framework (Step IV) deriving through the heterogeneous user groups that need to be accounted for during the design process, and the traces' physicality and wearing over time that might interfere with or create new meanings; 3) the users' willingness to interact (Steps II & IV); and 4) similarly, with the interface affordance considering touch gesture interaction (Steps II & IV). These points show the complexity of applying the *Traces in Use* design concept to contextualize urban interfaces due to the multiple stakeholders and heterogeneous user groups. Furthermore, they emphasize the diverging design requirements when comparing private and public contexts.

7.3.2 Traces in Use Support Individual Sense-Making and the Communication of Shared Place Meaning. The meaning of public, urban places may differ for every user [37], which makes it challenging to design for a common, shared understanding among multiple users. Yet, our work showed that the *Traces in Use* concept supports communicating the shared meaning of places and fosters a shared understanding. For example, the foot imprints in the *Storyteller* triggered an implicit social connectedness to people who had seemingly interacted at the same place in past times. Similarly, the *Lion* positioned at the historical place triggered the connection to the local cultural custom and beliefs. Participants reflected on other people's practices and intentions in both cases, validating the traces' effect on users' sense-making. Accordingly, the *Traces in Use* design concept can trigger individual users' sense-making and converge individual meanings into a shared place meaning.

7.3.3 Traces Help to Physically Embed Interfaces While Fostering a Place's Atmosphere. Field study participants (Step IV) perceived all of our interfaces as easy to ignore and suitable for the respective place (see Figure 9). At the Historical Square, participants imagined past scenarios, for example, one participant speculated that *"perhaps the court staff was already standing here[...]."*, P28 (B). It shows that our *Traces in Use* interfaces supported the atmosphere of the places and triggered users' imagination beyond the contemporary context. It aligns with the results in Step III, in which the experts described traces as elements that can embody history and authenticity. Both of these characteristics further support the design of unobtrusive and contextualized interfaces. Thus, *Traces in Use* interfaces can support a public place's atmosphere and meaning depending on its making and physical embeddedness onsite.

7.4 *Traces in Use* as a Design Concept

Lastly, we want to discuss the *Traces in Use* design concept independently from the urban interaction design situations presented here, to reflect on its relation to other theoretical concepts and its applicability in other contexts. To do so, we draw on comparisons to strong design concepts, which reside between theory and specific design instances [51]. We discuss the *Traces in Use* concept in relation to other (strong) concepts (e.g., social signifiers [79]) – a step which Höök and Löwgren [51] refer to as "horizontal grounding" and that is essential for intermediate-level knowledge construction. We further demonstrate its applicability in other contexts and domains based on design theory ("vertical grounding").

7.4.1 Traces in Use Construed as Strong Design Concept. We saw in Steps I, II, and IV that traces are recognizable and can trigger shared understanding about their creation. This, one could argue, qualifies them on a conceptual level as a so-called living pattern language [2]. However, Alexander et al. [2]'s influential work on patterns describes high-level repeated and static constructs, such as "street windows" or "tree places" in urban developments. In contrast, the *Traces in Use* design concept considers design features (traces) that derive from the interactions and behavior of individuals and masses of people with places and objects. Thus, traces grow and develop organically compared to Alexander et al. [2]'s structured pattern language. This sets the *Traces in Use* concept in relation to strong design concepts, which Höök and Löwgren [51] define as concerning a dynamic, changing gestalt that is part of a carrier. Further, we argue that our concept classifies also in the following regards based on the criteria presented in Höök and Löwgren [51]:

- "It concerns the dynamic gestalt of an interaction design" in the form of being generated through (artificial) interactions, influencing users' interaction.
- Traces in Use develop over time and use and reflect common behavior of multiple or individual user(s).
- The choice of the trace type and making can be realized in various ways.
- The traces are design elements that reflect socio-cultural meaning.
- The concept has been applied in other domain contexts in prior work: e.g., in VR to increase social presence and awareness [12, 43] and in private households contexts [98, 99].

Höök and Löwgren [51]'s criteria for a strong design concept additionally entails that "it resides on an abstraction level above particular instances". We cannot give a clear response to this point because the making of the material traces does require balancing certain attributes, e.g., their shape, color, and level of smoothness. Yet, there are still a lot of possible variabilities. For example, a touch trace could look like the ones integrated into our Lion interface. However, it could also look different depending on the material choices and the trace's outline because it was generated from more right-hand users than left-handed ones. In that sense, there are aspects that characterize traces that should stay consistent for the particular trace type but they can still be applied in many different ways.

7.4.2 Traces in Use in Relation To Other (Strong) Concepts. Considering the results throughout our work, traces seem to be a specific type of social signifier [61, 79]. We see this connection because the traces are always linked to a prior human interaction, and thus, embody social meaning by nature, which is a relevant characteristic of social signifiers. Furthermore, as confirmed in Step IV and in related work, they allow for implicit social awareness [18, 77], sense-making [56, 101], and meaning-making [20, 99] for shared contexts. They are meaningful, which is a characteristic of a social signifier [79] and, in parallel, enable meaningful relations to other dimensions [86].

Prior work has presented other similar concepts, such as “social cues” [77], “traces of time, use and skill” [89], etc. These concepts overlap in their design intentions and design feature characteristics with the *Traces in Use* concept. Applying digital traces, Mäkelä et al. [70], for example, revealed touch traces of prior users on a pervasive display for hygiene purposes. In other examples, Hespanhol and Dalsgaard [40] and Monastero and McGookin [77] projected AR traces to reveal people’s movements in space (e.g., in an office [77]). Another related strong concept is *social navigation*, which presents users with social cues that influence navigation decisions [18, 51, 52]. Contexts can then be spatial navigation [73], websites [74] and other examples [19]. The concept overlaps with the *Traces in Use* concept: e.g., in Kim et al. [62]’s work, the authors introduce a system that makes use of previous users’ annotation in e-books to help users navigate and find potentially interesting parts. In this example, the annotations can be seen as traces of previous interactions, or traces of use. Differences between those two concepts show, for example, in their foci in which the *Traces in Use* reveal and communicate the relations between the surroundings, other people, and the interface to connect users on a social and cultural level. In contrast, the *social navigation* aims to support users in making decisions about their own actions based on prior users’ activities. Nonetheless, both aim to support sense-making by using traces of social behaviors and activities. The similarity to other concepts further strengthens the *Traces in Use* as a strong concept considering its “horizontal grounding” [51].

7.4.3 Traces in Use in Cross-Reality (XR). Further, strong design concepts incorporate a core idea that is transferable across particular use situations and application domains and stays on a certain level of abstraction [51]. In this regard, we argue that the *Traces in Use* concept and similar concepts such as “social traces” [93], “markers of experiences” [86], or “temporal patterns” [89], have already been explored in different usage context (e.g., personal belongings, in the home, and now in an urban context) and for different purposes (e.g., trigger intimate, personal vs. shared meaning-making).

We started exploring and validating the *Traces in Use* for virtual environments in our previously published work [43]. For VR, prior work aimed to increase asynchronous social awareness and presence in VR [12, 43], i.e., we explored and validated the traces for virtual environments [43]. Further, in Chow et al. [12] traces of use appeared in the form of moving objects within a VR scene that had not been moved by the user but by others in-between visits. Accordingly, the traces keep their functionality as social signifiers in digital and virtual worlds, allowing the user to create meaningful connections to other users’ activities within the shared space. In each of these examples, the traces fostered social awareness and sense- and meaning-making by enabling users to understand the experience beyond the individual interaction experience. They also show the vast range of research applying traces in one way or another without a formalized concept, where we see the potential of the *Traces in Use* to provide a common ground. For example, we see under-explored research potential in exploring the traces as reality connectors along the Reality-Virtuality continuum, the spectrum of technologies and interfaces from physical to virtual reality [75, 96]. Creating systems to allow for asymmetric social connections and awareness is one of the big challenges in XR research (e.g., [32, 36, 81]). Applying the *Traces in Use* design concept along the continuum could potentially respond to these challenges. But it also introduces multiple research questions, such as how traces would change when transferring them from physical to virtual worlds. Or what are the interactions that traces in AR or VR result from, and how do they relate and compare to physical traces? For example, transferring the tangible trace characteristics presented in this work into other realities will present technical challenges such as identifying feasible substitutes. Similarly, the meaning and nature of virtual places differ a lot from, for example, urban places in the ‘real’ world. These differences raise the question of to what extent the concept can be applied to contextualize interfaces in other realities.

There are multiple application contexts and domains that apply traces or similar concepts. This grounds the *Traces in Use* concept vertically and strengthens its relatedness to being a strong design concept. Consequently, the *Traces in Use* design concept already resembles a strong design concept on various levels but will need further exploration to reaffirm this status. Yet, as introduced above, there are still various gaps mentioned that further provide multiple research opportunities to explore the concept further, particularly for use cases in other realities or along the Reality-Virtuality continuum. This also includes grounding it into theory.

7.5 Limitations and Future Work

Our work sets a strong focus on creating interfaces with a physical trace design, excluding other technologies such as augmented (AR) or mixed reality (MR) traces. Future work could bridge this gap and explore the *Traces in Use* concept for MR contexts and traces. Additionally, we tested the interfaces in Step IV with recruited participants and instructed profiles over a short period of time and at two places only. Future work should therefore evaluate their effectiveness over time and continued use. Also, the field results showed that we did not fully achieve to contextualize all interfaces on the same level for the two places. Yet, through this, we learned about the close inter-dependencies of the different contextualization perspectives, which requires developing approaches and methods to evaluate each perspective independently. Regarding the making of *Traces in Use* interfaces, Steps II and IV also identified the challenge of balancing the traces' naturalness with their usability and contextualization effect. Further exploration is needed on how to balance the traces' aesthetics (Step IV) and shape irregularity (Step II) so that the interface clearly affords the intended interactions while appearing in the *Traces in Use* design. Lastly, we currently ignore traces caused by other non-human agents such as the urban wildlife [13, 27] and autonomous urban robots [50]. We see the potential for future work to explore traces of non-human stakeholders sharing the same environment as people, in terms of their meaning and, in the case of traces caused by robots, their computational aesthetics.

8 SUMMARY

In our work, we present the development and evaluation of the *Traces in Use* design concept for the contextualization of urban interfaces. Based on collected natural, urban traces of use examples natural (Step I), we explored dimensions and characteristics relevant for the trace designs (Step II + IV a). We further set the dimensions into relation with each other in a *Traces in Use* framework, which we evaluated with experts (Step III) and in the design process of two empirical field studies (Step IV). Our results confirmed the framework as a useful tool to support the creation of contextualized urban interfaces using the *Traces in Use* design concept. Furthermore, the results identified the concept as an approach to physically embed interfaces that comply with heterogeneous user group needs by capturing the attention of interested users but being easy to ignore for passers-by / non-users. As such, our work contributes to two ongoing challenges within Urban IxD and extends prior work, for example, Wouters [111] by adding the material layer to contextualization perspectives content, carrier, and environment. Besides the contextualization of urban interfaces, we see the potential for the *Traces in Use* concept to similarly support the contextualization of an individual or shared interfaces and environments in other contexts, i.e., VR. In future steps, we aim to extend the concept of virtual, digital, and hybrid traces to foster sense- and meaning-making beyond the physical world.

REFERENCES

[1] Proton Technologies AG. 2020(last visited Mar. 20th 2022.). General Data Protection Regulation Information. https://https://gdpr.eu/

[2] Christopher Alexander, Sara Ishikawa, and Murray Silverstein. 1977. *A Pattern Language: Towns, Buildings, Construction.* Oxford University Press, New York.

[3] Susana Alves. 2014. Affordances of Historic Urban Landscapes: An Ecological Understanding of Human Interaction with the Past. *European Spatial Research and Policy* 21 (12 2014). https://doi.org/10.1515/esrp-2015-0002

[4] Adam Badawy, Emilio Ferrara, and Kristina Lerman. 2018. Analyzing the Digital Traces of Political Manipulation: The 2016 Russian Interference Twitter Campaign. In *Proceedings of the 2018 IEEE/ACM International Conference on Advances in Social Networks Analysis and Mining* (Barcelona, Spain) *(ASONAM '18)*. IEEE Press, 258–265.

[5] Jeffrey Bardzell, Shaowen Bardzell, Peter Dalsgaard, Shad Gross, and Kim Halskov. 2016. Documenting the Research Through Design Process. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 96–107. https://doi.org/10.1145/2901790.2901859

[6] Weston Baxter, Marco Aurisicchio, and Peter Childs. 2016. Materials, use and contaminated interaction. *Materials & Design* 90 (01 2016). https://doi.org/10.1016/j.matdes.2015.04.019

[7] Doug A. Bowman, Ryan P. McMahan, and Eric D. Ragan. 2012. Questioning Naturalism in 3D User Interfaces. *Commun. ACM* 55, 9 (Sept. 2012), 78–88. https://doi.org/10.1145/2330667.2330687

[8] Virginia Braun and Victoria Clarke. 2017. Applied Qualitative Research in Psychology. *Applied Qualitative Research in Psychology* 0887, 2006 (2017). https://doi.org/10.1057/978-1-137-35913-1

[9] Virginia Braun, Victoria Clarke, Nikki Hayfield, and Gareth Terry. 2019. Thematic Analysis BT - Handbook of Research Methods in Health Social Sciences. (2019), 843–860. https://doi.org/10.1007/978-981-10-5251-4_103

[10] Glenda Amayo Caldwell, Mirko Guaralda, Jared Donovan, and Markus Rittenbruch. 2016. The InstaBooth: Making Common Ground for Media Architectural Design. In *Proceedings of the 3rd Conference on Media Architecture Biennale* (Sydney, Australia) *(MAB)*. Association for Computing Machinery, New York, NY, USA, Article 3, 8 pages. https://doi.org/10.1145/2946803.2946806

[11] Amber Case. 2015. *Calm technology : principles and patterns for non-intrusive design* (1 ed.). O'Reilly Media, Inc., Sebastopol. 15–17 pages. https://learning.oreilly.com/library/view/calm-technology/9781491925874/?ar

[12] Kevin Chow, Caitlin Coyiuto, Cuong Nguyen, and Dongwook Yoon. 2019. Challenges and Design Considerations for Multimodal Asynchronous Collaboration in VR. *Proc. ACM Hum.-Comput. Interact.* 3, CSCW, Article 40 (nov 2019), 24 pages. https://doi.org/10.1145/3359142

[13] Rachel Clarke, Sara Heitlinger, Ann Light, Laura Forlano, Marcus Foth, and Carl DiSalvo. 2019. More-than-Human Participation: Design for Sustainable Smart City Futures. *Interactions* 26, 3 (apr 2019), 60–63. https://doi.org/10.1145/3319075

[14] Jorgos Coenen, Maarten Houben, and Andrew Vande Moere. 2019. Citizen Dialogue Kit: Public Polling and Data Visualization Displays for Bottom-Up Citizen Participation. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion* (San Diego, CA, USA) *(DIS '19 Companion)*. Association for Computing Machinery, New York, NY, USA, 9–12. https://doi.org/10.1145/3301019.3325160

[15] H. Coolen and J. Meesters. 2012. Private and public green spaces: meaningful but different settings. *Journal of House and the Built Environment* 27 (2012), 49–67. https://doi.org/10.1007/s10901-011-9246-5

[16] Peter Dalsgaard. 2010. Research in and through Design: An Interaction Design Research Approach. In *Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction* (Brisbane, Australia) *(OZCHI '10)*. Association for Computing Machinery, New York, NY, USA, 200–203. https://doi.org/10.1145/1952222.1952265

[17] Peter Dalsgaard and Kim Halskov. 2010. Designing Urban Media FaçAdes: Cases and Challenges. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Atlanta, Georgia, USA) *(CHI '10)*. Association for Computing Machinery, New York, NY, USA, 2277–2286. https://doi.org/10.1145/1753326.1753670

[18] A. Dieberger, P. Dourish, K. Höök, P. Resnick, and A. Wexelblat. 2000. Social Navigation: Techniques for Building More Usable Systems. *Interactions* 7, 6 (nov 2000), 36–45. https://doi.org/10.1145/352580.352587

[19] Paul DiGioia and Paul Dourish. 2005. Social Navigation as a Model for Usable Security. In *Proceedings of the 2005 Symposium on Usable Privacy and Security* (Pittsburgh, Pennsylvania, USA) *(SOUPS '05)*. Association for Computing Machinery, New York, NY, USA, 101–108. https://doi.org/10.1145/1073001.1073011

[20] Tao Dong, Mark S. Ackerman, and Mark W. Newman. 2014. "If These Walls Could Talk": Designing with Memories of Places. In *Proceedings of the 2014 Conference on Designing Interactive Systems* (Vancouver, BC, Canada) *(DIS '14)*. Association for Computing Machinery, New York, NY, USA, 63–72. https://doi.org/10.1145/2598510.2598605

[21] Paul Dourish. 2006. Re-Space-Ing Place: "Place" and "Space" Ten Years On. In *Proceedings of the 2006 20th Anniversary Conference on Computer Supported Cooperative Work* (Banff, Alberta, Canada) *(CSCW '06)*. Association for Computing Machinery, New York, NY, USA, 299–308. https://doi.org/10.1145/1180875.1180921

[22] Omid Ettehadi, Fraser Anderson, Adam Tindale, and Sowmya Somanath. 2021. *Documented: Embedding Information onto and Retrieving Information from 3D Printed Objects.* Association for Computing Machinery, New York, NY, USA.

[23] Gilles Fauconnier. 2001. Conceptual blending and analogy. *The Analogical Mind: Perspectives from Cognitive Science* (01 2001), 255–285.

[24] Patrick Tobias Fischer and Eva Hornecker. 2012. Urban HCI: Spatial Aspects in the Design of Shared Encounters for Media Facades. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 307–316. https://doi.org/10.1145/2207676.2207719

[25] Patrick Tobias Fischer, Anke von der Heide, Eva Hornecker, Sabine Zierold, Andreas Kästner, Felix Dondera, Matti Wiegmann, Fernando Millán, Jonas Lideikis, Aidas Čergelis, Reinaldo Verde, Christoph Drews, Till Fastnacht, Kai Gerrit Lünsdorf, Djamel Merad, Aryan Khosravani, and Hesam Jannesar. 2015. Castle-Sized Interfaces: An Interactive FaçAde Mapping. In *Proceedings of the 4th International Symposium on Pervasive Displays* (Saarbruecken, Germany) *(PerDis '15)*. Association for Computing Machinery, New York, NY, USA, 91–97. https://doi.org/10.1145/2757710.2757715

[26] Tom Fisher. 2004. What We Touch, Touches Us: Materials, Affects, and Affordances. *Design Issues* 20 (09 2004), 20–31. https://doi.org/10.1162/0747936042312066

[27] Marcus Foth and Glenda Amayo Caldwell. 2018. More-than-Human Media Architecture. In *Proceedings of the 4th Media Architecture Biennale Conference* (Beijing, China) *(MAB18)*. Association for Computing Machinery, New York, NY, USA, 66–75. https://doi.org/10.1145/3284389.3284495

[28] Jacinta Francis, Billie Giles-Corti, Lisa Wood, and Matthew Knuiman. 2012. Creating Sense of Community: The role of public space. *Journal of Environmental Psychology* 32 (12 2012), 401–409. https://doi.org/10.1016/j.jenvp.2012.07.002

[29] Joel Fredericks, Luke Hespanhol, and Martin Tomitsch. 2016. Not Just Pretty Lights: Using Digital Technologies to Inform City Making. In *Proceedings of the 3rd Conference on Media Architecture Biennale* (Sydney, Australia) *(MAB)*. Association for Computing Machinery, New York, NY, USA, Article 7, 9 pages. https://doi.org/10.1145/2946803.2946810

[30] Ben Fry and Casey Reas. 2011(last visited August. 10th 2022.). Processing. https://processing.org

[31] Bill Gaver and John Bowers. 2012. Annotated Portfolios. *Interactions* 19, 4 (jul 2012), 40–49. https://doi.org/10.1145/2212877.2212889

[32] Ceenu George, An Ngo Tien, and Heinrich Hussmann. 2020. Seamless, Bi-directional Transitions along the Reality-Virtuality Continuum: A Conceptualization and Prototype Exploration. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 412–424. https://doi.org/10.1109/ISMAR50242.2020.00067

[33] Elisa Giaccardi and Elvin Karana. 2015. Foundations of Materials Experience: An Approach for HCI. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2447–2456. https://doi.org/10.1145/2702123.2702337

[34] Condens Insights GmbH. 2021(last visited Feb. 20th 2022.). Condens. https://condens.io

[35] Ted Grover and Gloria Mark. 2017. Digital Footprints: Predicting Personality from Temporal Patterns of Technology Use. In *Proceedings of the 2017 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2017 ACM International Symposium on Wearable Computers* (Maui, Hawaii) *(UbiComp '17)*. Association for Computing Machinery, 41–44. https://doi.org/10.1145/3123024.3123139

[36] Jan Gugenheimer, Evgeny Stemasov, Julian Frommel, and Enrico Rukzio. 2017. ShareVR: Enabling Co-Located Experiences for Virtual Reality between HMD and Non-HMD Users. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4021–4033. https://doi.org/10.1145/3025453.3025683

[37] Per Gustafson. 2001. Meanings of Place: Everyday Experience And Theoretical Conceptualization. *Journal of Environmental Psychology* 21, 1 (2001), 5–16. https://doi.org/10.1006/jevp.2000.0185

[38] Patrick Harms. 2019. Automated Usability Evaluation of Virtual Reality Applications. *ACM Trans. Comput.-Hum. Interact.* 26, 3, Article 14 (apr 2019), 36 pages. https://doi.org/10.1145/3301423

[39] Marc Hassenzahl, Michael Burmester, and Franz Koller. 2003. *AttrakDiff: Ein Fragebogen zur Messung wahrgenommener hedonischer und pragmatischer Qualität.* Vieweg+Teubner Verlag, Wiesbaden, 187–196. https://doi.org/10.1007/978-3-322-80058-9_19

[40] Luke Hespanhol and Peter Dalsgaard. 2015. Social Interaction Design Patterns for Urban Media Architecture. In *Human-Computer Interaction – INTERACT 2015*, Julio Abascal, Simone Barbosa, Mirko Fetter, Tom Gross, Philippe Palanque, and Marco Winckler (Eds.). Springer International Publishing, Cham, 596–613.

[41] Luke Hespanhol and Martin Tomitsch. 2015. Strategies for Intuitive Interaction in Public Urban Spaces. *Interacting with Computers* 27, 3 (01 2015), 311–326. https://doi.org/10.1093/iwc/iwu051 arXiv:https://academic.oup.com/iwc/article-pdf/27/3/311/6957736/iwu051.pdf

[42] Linda Hirsch, Eleni Economidou, Irina Paraschivoiu, and Tanja Döring. 2022. Material Meets the City: A Materials Experience Perspective on Urban Interaction Design. *Interactions* 29, 1 (jan 2022), 58–63. https://doi.org/10.1145/3501358

[43] Linda Hirsch, Ceenu George, and Andreas Butz. 2022. Traces in Virtual Environments: A Framework and Exploration to Conceptualize the Design of Social Virtual Environments. In *Proceedings of the 2022 ISMAR* (Singapor, Singapor) *(ISMAR '22)*. IEEE, tbd, Article 00, 00 pages. https://doi.org/tbd

[44] Linda Hirsch, Beat Rossmy, Florian Bemmann, and Andreas Butz. 2020. Affordances Based on Traces of Use in Urban Environments. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Sydney NSW, Australia) *(TEI '20)*. Association for Computing Machinery, New York, NY, USA, 729–742. https://doi.org/10.1145/3374920.3375007

[45] Linda Hirsch, Beat Rossmy, and Andreas Butz. 2021. Shaping Concrete for Interaction. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 6, 11 pages. https://doi.org/10.1145/3430524.3440625

[46] Linda Hirsch, Christina Schneegass, Robin Welsch, and Andreas Butz. 2021. To See or Not to See: Exploring Inattentional Blindness for the Design of Unobtrusive Interfaces in Shared Public Places. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5, 1, Article 15 (mar 2021), 25 pages. https://doi.org/10.1145/3448123

[47] Linda Hirsch, Robin Welsch, Beat Rossmy, and Andreas Butz. 2022. Embedded AR Storytelling Supports Active Indexing at Historical Places. In *Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Daejeon, Republic of Korea) *(TEI '22)*. Association for Computing Machinery, New York, NY, USA, 19 pages. https://doi.org/10.1145/3490149.3501328

[48] Marius Hoggenmueller, Luke Hespanhol, and Martin Tomitsch. 2020. Stop and Smell the Chalk Flowers: A Robotic Probe for Investigating Urban Interaction with Physicalised Displays. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376676

[49] Marius Hoggenmueller, Luke Hespanhol, Alexander Wiethoff, and Martin Tomitsch. 2019. Self-Moving Robots and Pulverized Urban Displays: Newcomers in the Pervasive Display Taxonomy. In *Proceedings of the 8th ACM International Symposium on Pervasive Displays* (Palermo, Italy) *(PerDis '19)*. Association for Computing Machinery, New York, NY, USA, Article 1, 8 pages. https://doi.org/10.1145/3321335.3324950

[50] Marius Hoggenmueller, Martin Tomitsch, and Joel Fredericks. 2020. Bringing Sustainability-Sensitivity into the Design of Public Interfaces: Opportunities and Challenges. (05 2020). Position paper presented at the SelfSustainableCHI workshop in conjunction with CHI Conference on Human Factors in Computing Systems.

[51] Kristina Höök and Jonas Löwgren. 2012. Strong Concepts: Intermediate-Level Knowledge in Interaction Design Research. *ACM Trans. Comput.-Hum. Interact.* 19, 3, Article 23 (oct 2012), 18 pages. https://doi.org/10.1145/2362364.2362371

[52] Kristina Höök, Alan Wexelblat, and Alan Munro. 2000. Social Navigation: A Design Approach?. In *CHI '00 Extended Abstracts on Human Factors in Computing Systems* (The Hague, The Netherlands) *(CHI EA '00)*. Association for Computing Machinery, New York, NY, USA, 375. https://doi.org/10.1145/633292.633522

[53] Eva Hornecker. 2016. The To-and-Fro of Sense Making: Supporting Users' Active Indexing in Museums. *ACM Trans. Comput.-Hum. Interact.* 23, 2, Article 10 (may 2016), 48 pages. https://doi.org/10.1145/2882785

[54] Eva Hornecker and Matthias Stifter. 2006. Learning from Interactive Museum Installations about Interaction Design for Public Settings. In *Proceedings of the 18th Australia Conference on Computer-Human Interaction: Design: Activities, Artefacts and Environments* (Sydney, Australia) *(OZCHI '06)*. Association for Computing Machinery, New York, NY, USA, 135–142. https://doi.org/10.1145/1228175.1228201

[55] Cheng-Kang Hsieh, Longqi Yang, Honghao Wei, Mor Naaman, and Deborah Estrin. 2016. Immersive Recommendation: News and Event Recommendations Using Personal Digital Traces. In *Proceedings of the 25th International Conference on World Wide Web* (Montréal, Québec, Canada) *(WWW '16)*. International World Wide Web Conferences Steering Committee, Republic and Canton of Geneva, CHE, 51–62. https://doi.org/10.1145/2872427.2883006

[56] Caroline Hummels and Jelle van Dijk. 2015. Seven Principles to Design for Embodied Sensemaking. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (Stanford, California, USA) *(TEI '15)*. Association for Computing Machinery, New York, NY, USA, 21–28. https://doi.org/10.1145/2677199.2680577

[57] Elvin Karana, Bahar Barati, Valentina Rognoli, and Anouk Zeeuw van der Laan. 2015. Material Driven Design (MDD): A Method to Design for Material Experiences. *International Journal of Design* in press (05 2015).

[58] Elvin Karana, Owain Pedgley, and Valentina Rognoli. 2015. On Materials Experience. *Design Issues* 31, 3 (2015), 16–27. http://www.jstor.org/stable/43829331

[59] Elvin Karana, Owain Pedgley, Valentina Rognoli, and and authors. 2013. *Materials Experience: Fundamentals of Materials and Design.*

[60] Hyunjung Kim and Woohun Lee. 2009. Designing Unobtrusive Interfaces with Minimal Presence. In *CHI '09 Extended Abstracts on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI EA '09)*. Association for Computing Machinery, New York, NY, USA, 3673–3678. https://doi.org/10.1145/1520340.1520553

[61] Jingoog Kim and Mary Lou Maher. 2019. Metaphors, Signifiers, Affordances, and Modalities for Designing Mobile and Embodied Interactive Systems. In *Proceedings of the 31st Australian Conference on Human-Computer-Interaction* (Fremantle, WA, Australia) *(OZCHI'19)*. Association for Computing Machinery, New York, NY, USA, 542–545. https://doi.org/10.1145/3369457.3369527

[62] Jae-Kyung Kim, Rosta Farzan, and Peter Brusilovsky. 2008. Social Navigation and Annotation for Electronic Books. In *Proceedings of the 2008 ACM Workshop on Research Advances in Large Digital Book Repositories* (Napa Valley, California, USA) *(BooksOnline '08)*. Association for Computing Machinery, New York, NY, USA, 25–28. https://doi.org/10.1145/1458412.1458421

[63] Henrik Korsgaard, Nicolai Brodersen Hansen, Ditte Basballe, Peter Dalsgaard, and Kim Halskov. 2012. Odenplan: A Media FaçAde Design Process. In *Proceedings of the 4th Media Architecture Biennale Conference: Participation* (Aarhus, Denmark) *(MAB '12)*. Association for Computing Machinery, New York, NY, USA, 23–32. https://doi.org/10.1145/2421076.2421081

[64] Elad Kravi. 2016. Understanding User Behavior From Online Traces. In *Proceedings of the 2016 on SIGMOD'16 PhD Symposium* (San Francisco, California, USA) *(SIGMOD'16 PhD)*. Association for Computing Machinery, New York, NY, USA, 27–31. https://doi.org/10.1145/2926693.2929901

[65] Bi Li, Boyu Chen, Yan Wu, Juan Wang, Xueming Yan, and Yahui Yang. 2020. Identifying the Motives of Using Weibo from Digital Traces. In *Proceedings of the 4th International Conference on Natural Language Processing and Information Retrieval* (Seoul, Republic of Korea) *(NLPIR 2020)*. Association for Computing Machinery, New York, NY, USA, 169–172. https://doi.org/10.1145/3443279.3443294

[66] Szu-Yu (Cyn) Liu, Jeffrey Bardzell, and Shaowen Bardzell. 2019. Decomposition as Design: Co-Creating (with) Natureculture. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, 605–614. https://doi.org/10.1145/3294109.3295653

[67] Dan Lockton, Delanie Ricketts, Shruti Aditya Chowdhury, and Chang Hee Lee. 2017. Exploring Qualitative Displays and Interfaces. In *Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI EA '17)*. Association for Computing Machinery, New York, NY, USA, 1844–1852. https://doi.org/10.1145/3027063.3053165

[68] Parker Corporation LP. 2006 (last visited Feb. 20th 2022). GoTranskript. https://gotranscript.com

[69] Rachel Macrorie, Simon Marvin, and Aidan While. 2021. Robotics and automation in the city: a research agenda. *Urban Geography* 42, 2 (2021), 197–217. https://doi.org/10.1080/02723638.2019.1698868

[70] Ville Mäkelä, Jonas Winter, Jasmin Schwab, Michael Koch, and Florian Alt. 2022. Pandemic Displays: Considering Hygiene on Public Touchscreens in the Post-Pandemic Era. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 284, 12 pages. https://doi.org/10.1145/3491102.3501937

[71] A.B. Markman and D. Gentner. 2000. Structure Mapping in the Comparison Process. *The American Journal of Psychology* 113, 4, Article 179 (nov 2000), 501-538 pages. https://doi.org/10.2307/1423470

[72] Jon Mason. 2014. 'Does it Make Sense' or 'What Does it Mean'? *Proceedings of the 22nd International Conference on Computers in Education, ICCE 2014*.

[73] Felix Mata and Christophe Claramunt. 2014. A Social Navigation Guide Using Augmented Reality. In *Proceedings of the 22nd ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems* (Dallas, Texas) *(SIGSPATIAL '14)*. Association for Computing Machinery, New York, NY, USA, 541–544. https://doi.org/10.1145/2666310.2666364

[74] Robert Mertens, Rosta Farzan, and Peter Brusilovsky. 2006. Social Navigation in Web Lectures. In *Proceedings of the Seventeenth Conference on Hypertext and Hypermedia* (Odense, Denmark) *(HYPERTEXT '06)*. Association for Computing Machinery, New York, NY, USA, 41–44. https://doi.org/10.1145/1149941.1149950

[75] Paul Milgram, Haruo Takemura, Akira Utsumi, and Fumio Kishino. 1995. Augmented reality: a class of displays on the reality-virtuality continuum. In *Telemanipulator and Telepresence Technologies*, Hari Das (Ed.), Vol. 2351. International Society for Optics and Photonics, SPIE, 282 – 292. https://doi.org/10.1117/12.197321

[76] Miro. 2011(last visited Feb. 20th 2022). Miro. https://miro.com

[77] Beatrice Monastero and David K. McGookin. 2018. *Traces: Studying a Public Reactive Floor-Projection of Walking Trajectories to Support Social Awareness.* Association for Computing Machinery, New York, NY, USA, 1–13.

[78] Gemma Moore, Ben Croxford, Mags Adams, Mohamed Refaee, Trevor Cox, and Steve Sharples. 2008. The photo-survey research method: capturing life in the city. *Visual Studies* 23 (04 2008), 50–62. https://doi.org/10.1080/14725860801908536

[79] Donald A. Norman. 2008. THE WAY I SEE IT Signifiers, Not Affordances. *Interactions* 15, 6 (nov 2008), 18–19. https://doi.org/10.1145/1409040.1409044

[80] Dietmar Offenhuber and Susanne Seitinger. 2014. Over the Rainbow: Information Design for Low-Resolution Urban Displays. In *Proceedings of the 2nd Media Architecture Biennale Conference: World Cities* (Aarhus, Denmark) *(MAB '14)*. Association for Computing Machinery, New York, NY, USA, 40–47. https://doi.org/10.1145/2682884.2682886

[81] Kaitlyn M. Ouverson and Stephen B. Gilbert. 2021. A Composite Framework of Co-Located Asymmetric Virtual Reality. *Proc. ACM Hum.-Comput. Interact.* 5, CSCW1, Article 5 (apr 2021), 20 pages. https://doi.org/10.1145/3449079

[82] Callum Parker, Martin Tomitsch, Nigel Davies, Nina Valkanova, and Judy Kay. 2020. Foundations for Designing Public Interactive Displays That Provide Value to Users. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376532

[83] Anjul Patney, Marco Salvi, Joohwan Kim, Anton Kaplanyan, Chris Wyman, Nir Benty, David Luebke, and Aaron Lefohn. 2016. Towards Foveated Rendering for Gaze-Tracked Virtual Reality. *ACM Trans. Graph.* 35, 6, Article 179 (nov 2016), 12 pages. https://doi.org/10.1145/2980179.2980246

[84] Diego Paez-Granados Pericle Salvini and Aude Billard. 2022. Safety Concerns Emerging from Robots Navigating in Crowded Pedestrian Areas. *International Journal of Social Robotics* 14 (2022), 441–462. https://doi.org/10.1007/s12369-021-00796-4

[85] Christopher M. Raymond, Marketta Kyttä, and Richard Stedman. 2017. Sense of Place, Fast and Slow: The Potential Contributions of Affordance Theory to Sense of Place. *Frontiers in Psychology* 8 (2017), 1674. https://doi.org/10.3389/fpsyg.2017.01674

[86] Holly Robbins, Elisa Giaccardi, and Elvin Karana. 2016. Traces as an Approach to Design for Focal Things and Practices. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction* (Gothenburg, Sweden) *(NordiCHI '16)*. Association for Computing Machinery, New York, NY, USA, Article 19, 10 pages. https://doi.org/10.1145/2971485.2971538

[87] Valentina Rognoli, Venere Ferraro, and Stefano Parisi. 2021. *ICS Materiality: the phenomenon of interactive, connected, and smart materials as enablers of new materials experiences.*

[88] Bernice Rogowitz, Laura Perovich, Yuke Li, Bjorn Kierulf, and Dietmar Offenhuber. 2021. Touching Art – A Method for Visualizing Tactile Experience. In *This manuscript was presented at alt.VIS, a workshop co-located with IEEE VIS 2021 (held virtually).*

[89] Daniela K. Rosner, Miwa Ikemiya, Diana Kim, and Kristin Koch. 2013. Designing with traces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '13*. ACM Press, New York, New York, USA, 1649–1658. https://doi.org/10.1145/2470654.2466218

[90] Beat Roßmy. 2021. *Designing speculative artifacts.* Ph. D. Dissertation. http://nbn-resolving.de/urn:nbn:de:bvb:19-294132

[91] Darshan Santani, Joan-Isaac Biel, Florian Labhart, Jasmine Truong, Sara Landolt, Emmanuel Kuntsche, and Daniel Gatica-Perez. 2016. The Night is Young: Urban Crowdsourcing of Nightlife Patterns. In *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (Heidelberg, Germany) *(UbiComp '16)*. Association for Computing Machinery, New York, NY, USA, 427–438. https://doi.org/10.1145/2971648.2971713

[92] Susanne Schmidt, Sven Zimmermann, Celeste Mason, and Frank Steinicke. 2022. Simulating Human Imprecision in Temporal Statements of Intelligent Virtual Agents. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 422, 15 pages. https://doi.org/10.1145/3491102.3517625

[93] A. Schütte. 1998. Patina : layering a history-of-use on digital objects.

[94] Susanne Seitinger, Daniel S. Perry, and William J. Mitchell. 2009. Urban Pixels: Painting the City with Light. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Boston, MA, USA) *(CHI '09)*. Association for Computing Machinery, New York, NY, USA, 839–848. https://doi.org/10.1145/1518701.1518829

[95] Michele Settanni, Danny Azucar, and Davide Marengo. 2018. Predicting Individual Characteristics from Digital Traces on Social Media: A Meta-Analysis. *Cyberpsychology, Behavior, and Social Networking* 21 (02 2018). https://doi.org/10.1089/cyber.2017.0384

[96] Richard Skarbez, Missie Smith, and Mary C. Whitton. 2021. Revisiting Milgram and Kishino's Reality-Virtuality Continuum. *Frontiers in Virtual Reality* 2 (2021). https://doi.org/10.3389/frvir.2021.647997

[97] Martin Tomitsch. 2018. *Making Cities Smarter: Designing Interactive Urban Applications*.

[98] Wenn-Chieh Tsai, Daniel Orth, and Elise van den Hoven. 2017. Designing Memory Probes to Inform Dialogue. In *Proceedings of the 2017 Conference on Designing Interactive Systems - DIS '17*. ACM Press, New York, New York, USA, 889–901. https://doi.org/10.1145/3064663.3064791

[99] Wenn-Chieh Tsai and Elise van den Hoven. 2018. Memory Probes: Exploring Retrospective User Experience Through Traces of Use on Cherished Objects. *International Journal of Design* 12, 3 (2018), 57–72. http://www.ijdesign.org/index.php/IJDesign/article/view/2900

[100] Jane Turner and Ann Morrison. 2021. Designing Slow Cities for More Than Human Enrichment: Dog Tales—Using Narrative Methods to Understand Co-Performative Place-Making. *Multimodal Technologies and Interaction* 5, 1 (2021). https://doi.org/10.3390/mti5010001

[101] Jelle van Dijk. 2013. *Creating traces, sharing insight: Explorations in embodied cognition design*. Ph. D. Dissertation. Eindhoven University of Technology. https://doi.org/10.6100/IR759609

[102] Andrew Vande Moere and Dan Hill. 2012. Designing for the Situated and Public Visualization of Urban Data. *Journal of Urban Technology* (2012). https://doi.org/10.1080/10630732.2012.698065

[103] Andrew Vande Moere and Niels Wouters. 2012. The Role of Context in Media Architecture. In *Proceedings of the 2012 International Symposium on Pervasive Displays* (Porto, Portugal) *(PerDis '12)*. Association for Computing Machinery, New York, NY, USA, Article 12, 6 pages. https://doi.org/10.1145/2307798.2307810

[104] Ron Wakkary. 2021. *Things We Could Design For More Than Human-Centered Worlds*.

[105] Honghao Wei, Cheng-Kang Hsieh, Longqi Yang, and Deborah Estrin. 2016. GroupLink: Group Event Recommendations Using Personal Digital Traces. In *Proceedings of the 19th ACM Conference on Computer Supported Cooperative Work and Social Computing Companion* (San Francisco, California, USA) *(CSCW '16 Companion)*. Association for Computing Machinery, New York, NY, USA, 110–113. https://doi.org/10.1145/2818052.2874338

[106] Alexander Wiethoff and Sven Gehring. 2012. Designing Interaction with Media FaçAdes: A Case Study. In *Proceedings of the Designing Interactive Systems Conference* (Newcastle Upon Tyne, United Kingdom) *(DIS '12)*. Association for Computing Machinery, New York, NY, USA, 308–317. https://doi.org/10.1145/2317956.2318004

[107] Alexander Wiethoff and Marius Hoggenmueller. 2017. Experiences Deploying Hybrid Media Architecture in Public Environments. In *Media Architecture: Using Information and Media as Construction Material*, Alexander Wiethoff and Heinrich Hussmann (Eds.). De Gruyter. https://doi.org/10.1515/9783110453874-008

[108] Alexander Wiethoff, Marius Hoggenmueller, Beat Rossmy, Linda Hirsch, Luke Hespanhol, and Martin Tomitsch. 2021. A Media Architecture Approach for Designing the Next Generation of Urban Interfaces. *IxD&A* 48, 9–32.

[109] Krzysztof Wodiczko, Anke von der Heide, Patrick Tobias Fischer, Timm Burkhardt, Roy Müller, Lea Brugnoli, Hala Ghatasheh, Sebastian Schuster, Christian Paffrath, Muzaffar Ali, Mark Eisenberg, Michael Ohaya, Christian Rene Manzano Schlamp, David Leroy, Eva Hornecker, Wolfgang Sattler, and Liz Bachhuber. 2017. Die Ermittler: A Dialogue about Displacement, Refuge, and Home. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia* (Stuttgart, Germany) *(MUM '17)*. Association for Computing Machinery, New York, NY, USA, 527–533. https://doi.org/10.1145/3152832.3156608

[110] Christine Wolf, Kathryn E. Ringland, and Gillian Hayes. 2019. Home Worlds: Situating Domestic Computing in Everyday Life Through a Study of DIY Home Repair. *Proc. ACM Hum.-Comput. Interact.* 3, CSCW, Article 161 (nov 2019), 22 pages. https://doi.org/10.1145/3359263

[111] Niels Wouters. 2016. *Contextualising Media Architecture: Design Approaches to Support Social and Architectural Relevance*. Ph. D. Dissertation. https://doi.org/10.13140/RG.2.2.11496.67840

[112] Niels Wouters, John Downs, Mitchell Harrop, Travis Cox, Eduardo Oliveira, Sarah Webber, Frank Vetere, and Andrew Vande Moere. 2016. Uncovering the Honeypot Effect: How Audiences Engage with Public Interactive Systems. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, Australia) *(DIS '16)*. Association for Computing Machinery, New York, NY, USA, 5–16. https://doi.org/10.1145/2901790.2901796

[113] Niels Wouters, Koenraad Keignaert, Jonathan Huyghe, and Andrew Vande Moere. 2016. Revealing the Architectural Quality of Media Architecture. In *Proceedings of the 3rd Conference on Media Architecture Biennale* (Sydney, Australia) *(MAB)*. Association for Computing Machinery, New York, NY, USA, Article 5, 4 pages. https://doi.org/10.1145/2946803.2946808

[114] Pengyi Zhang and Dagobert Soergel. 2014. Towards a comprehensive model of the cognitive process and mechanisms of individual sensemaking. *Journal of the Association for Information Science and Technology* 65, 9 (2014), 1733–1756. https://doi.org/10.1002/asi.23125

[115] Karolina M. Zielinska-Dabkowska. 2014. Critical Perspectives on Media Architecture: Is It Still Possible to Design Projects without Negatively Affecting Urban Nighttime Environments and Will the Future Remain Dynamic, Bright and Multi-Colored?. In *Proceedings of the 2nd Media Architecture Biennale Conference: World Cities* (Aarhus, Denmark) *(MAB '14)*. Association for Computing Machinery, New York, NY, USA, 101–108. https://doi.org/10.1145/2682884.2682895

[116] Inc. Zoom Video Communications. 2011(last visited July. 15th 2022.). Zoom. https://zoom.us

A AUTHOR STATEMENT

This paper is a consolidating contribution of novel and published work. The concept development in section 3 is based on two previous publications. The rest has yet to be published or is under concurrent submission elsewhere.

Step I is based on: Linda Hirsch, Beat Rossmy, Florian Bemmann, and Andreas Butz. 2020. Affordances Based on Traces of Use in Urban Environments. In Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '20). Association for Computing Machinery, New York, NY, USA, 729–742. doi: 10.1145/3374920.3375007. The pictorial comprises the picture collection, the focus group, and the online evaluation and shows in depth the different trace characteristics identified throughout the process. In addition to the published work, we added some citations from the expert interviews that were not cited in the pictorial. This difference is because pictorials are meant as image-based submissions with as little text as possible. Accordingly, these statements were part of our analysis but were not presented in the pictorial. Furthermore, the trace characteristics can all be found in the pictorial. Yet, we decided to present them here in one table (Table 1) and in combination with the results from Step II to avoid unnecessary repetitions.

Step II is based on: Linda Hirsch, Beat Rossmy, and Andreas Butz. 2021. 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, Article 6, 1–11. doi: 10.1145/3430524.3440625. We rephrased and summarized the content presented in the paper that we considered relevant for the *Traces in Use* concept development. Thus, the content of the corresponding section of this submission has entirely been published before but is, of course, rewritten for this submission.