Design Opportunities for Assistive and Social Technologies Situated in Space

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Abstract

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Computers are increasingly integrated into daily environments. Human interactions with computers become inseparable from interacting with physical spaces. I take a qualitative research approach to consider space as an integral part of understanding people, leading to design opportunities for technologies situated in space. My thesis presents the design opportunities for blind assistive technology to support exploratory navigation and physically-grounded social technology for remote connections. Studying space gives insights into how users and technologies situated in space interact with one another, how users perceive the physical space, and what behavioral patterns users display around the space while using technology. The insights contribute to constructing design implications from an underexplored creative angle and shed light on how spatial scenarios dynamically change preferences and opportunities in the design of future technologies.

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Chapter 1: Introduction

In Human-Computer Interaction, research concerns designing technology to meet users' information needs and designing the experience of information conveyance to users in a contextual situation. One of the contextual factors dynamically changes people's preferences in receiving and perceiving information is space. In prior research, space is often studied as an information input source to be collected and analyzed or as an interface for information output display. To explore design opportunities for information technologies, it is important to understand space as an integral part of understanding people, because people's interactive experience with these technologies is inherently situated in space. With my background in architecture, I have a unique sensibility to observe and design how people use, navigate, and perceive diverse forms of physical and social spaces.

In my thesis, I conduct two research projects to confront the question of understanding space and design opportunities for technologies situated in space. The first project concerns accessible assistive technology where the blind and low-vision users and the technology are situated in unfamiliar physical environments. The second project concerns social technology situated in remotely distributed but physically grounded social scenarios in long-distance relationships.

In Chapter 3, titled *"I Want to Figure Things Out"* [80], along with Gaurav Jain, we investigate visually impaired people(VIP)'s spatial intention when situated in unfamiliar physical environments and discover design opportunities for assistive technology in support for exploratory navigation. I ask the question of how VIPs would want to learn about the space they are situated in. Unlike the common approach in assistive technology to provide spatial information as turn-by-turn instructions, we find that VIP users do not want technology to constantly feed them with information and replace their autonomy of spatial engagement. Users intend to play an active role in exploring and gathering information in the physical space they are situated in. With this understanding, we recommend the design of future navigation assistive systems to facilitate spatial information, promote active engagement, and serve as educational tools to help VIPs build confidence in their O&M skills, thereby supporting VIPs' exploration in navigation.

In Chapter 4, titled *Social Wormholes*, along with Joanne Leong and Xingyu Liu, we explore the opportunity for ubiquitous computing to promote staying connected with friends in an environment-centered way, repurposing the surrounding spaces to serve as connection points. I ask the question of how people perceive remote spaces when given the power to create and customize multiple physically-grounded social connection points. The findings reveal that people adopt diverse perspectives of spatial awareness and the patterns of behaviors around ubiquitous social computing. Depending on the communication topics and social relationships, people perceive strong co-presence with people in remote spaces in some scenarios. In contrast, in other scenarios, people interpret the physical spatial context as a proxy for other people or shared activities. This understanding of people with respect to spaces suggests that future research on ubiquitous social computing should anticipate a mosaic of different perspectives co-existing in people's lives. Technology should be designed to respond with a mosaic of different types of connected artifacts.

Seeking to understand space as an integral part of understanding people gives insights into people's perceptions and behaviors in using technologies situated in space. The space-focused insights from this qualitative research approach contribute to constructing design implications from an underexplored creative angle and shed light on how spatial scenarios dynamically change preferences and opportunities in designing future technologies.

Chapter 2: Related Work

2.1 The Importance of Exploration in Navigation

Exploration involves incidental learning of a space which supports the ability to make in-situ navigation decisions [51]. While one gathers both *route* knowledge and *survey* knowledge when navigating environments, exploration is primarily supported via survey knowledge [56]. Route knowledge includes path from one point to another and landmarks along the path and is acquired via an egocentric reference frame (person-centered). In contrast, survey knowledge includes configuration of the space and is acquired via an allocentric reference frame (environment-centered).

Various strands of cognitive science research indicate the importance of exploration to navigation. Specifically, the ability to explore environments leads to two primary cognitive benefits: the formation of cognitive maps [116, 145] and the promotion of active engagement with the environment [28, 31]. Regarding the formation of cognitive maps, Tolman et al. [145] found that maps created via exploration can be accessed and used from any location in the environment and not just from specific places or routes. Regarding the promotion of active engagement, Chrastil et al. [28] report that playing an active role in spatial decision-making leads to a better spatial understanding of the environment. This understanding can be useful in many situations, such as when the need to find an alternative route arises [31]. In addition to these two benefits, many researchers have shown that the ability to explore unfamiliar environments can improve the development of cognitive abilities and improve overall brain health [103, 34, 90].

This body of work reveals the potential benefits that navigation assistance systems(NASs) could bring by facilitating exploration for VIPs. Since we do not yet understand how exactly NASs should be designed to support exploration for VIPs, our work aims to address this research gap.

2.2 Tools for Supporting Exploration in Navigation

Various navigation tools support VIPs' exploration in unfamiliar environments. Tactile maps have been shown to provide VIPs with a spatial representation of an environment via touch [44, 147, 1, 79, 141, 110, 42], enabling them to preview an unfamiliar environment before their visit [19, 78]. Another set of tools uses virtual reality (VR) for developing virtual environment systems that support VIPs' learning and exploration of both virtual [137, 159] and physical environments [91, 144, 160]. Many tools such as AIRA [7], VizWiz [18], and BeMyEyes [70] utilize crowdsourcing to connect VIPs with sighted people over the internet for real-time remote sighted assistance.

Within tools that support exploration, our work focuses on navigation assistance systems (NASs), which is defined as systems that provide users with real-time feedback about their surroundings and their location within the space to enable interactions for supporting navigation. Most NASs follow a turn-by-turn navigation approach to guide users to their destination via verbal descriptions [2, 45, 12, 109, 123, 124] or by acting as a metaphorical "guide dog" that users follow [62, 85, 84, 10, 119, 125, 128].

Several recent works in human-computer interaction (HCI) have argued for NASs to facilitate exploration in addition to turn-by-turn guidance. Nair et al. [111] recently highlighted the importance of exploration and the ability to look around when navigating, creating a system called NavStick for giving VIP players the ability to look around within adventure video games. Dey et al. [40, 39] show that even simple modifications in existing NAS interfaces that go beyond just providing turn-by-turn directions can help sighted people acquire spatial knowledge of an environment. Clemenson et al. [35] recently argued that NAS designers should rethink the role of turn-by-turn navigation systems so that they can facilitate active engagement with the world.

NAS developers have also made efforts to facilitate exploration [21, 118, 127, 107, 54]. In-Situ Audio Services (ISAS) [21] and NavCog3 [127], for example, announce nearby points of interest (POIs) via speech and 3D-spatialized audio either during a route (via "pushes") or via search ("pulls"). Microsoft Soundscape [107] places audio beacons directly at the destination instead of giving them instructions at every turn, allowing users to determine their own routes.

Although recent research has emphasized the crucial role that exploration plays in navigation and has made some notable contributions towards it, research in accessibility and cognitive science shows there is more to exploration than learning nearby POIs and the routes to destinations. Exploration in navigation includes learning about spaces and building an environment-centered cognitive map of spaces to make navigation decisions from [13, 68, 101, 133]. Before our community can ever develop NASs to support exploration, it is important for us to take a step back and gain a holistic understanding about what information VIPs need in order to explore and why VIPs find it difficult to gather this information in the first place. Hence, our work does not introduce new technology but instead aims to broaden our understanding of VIPs' needs and challenges around exploration.

2.3 Understanding VIPs' Navigation Needs and Challenges

Several studies have identified VIPs' information needs while navigating [3, 155, 122, 97, 17, 129, 61] and the challenges that VIPs face [53, 154, 43, 142, 153], but most of them are aimed at informing the design of NASs that support turn-by-turn navigation. Our focus, on the other hand, is to understand VIPs' information needs and challenges regarding *exploring* unfamiliar environments, which remains understudied [13].

Lewis et al. [97] interviewed a focus group of VIPs to determine user requirements for NASs, but only in the context of turn-by-turn navigation. Specifically, most of their findings correlate with information about POIs, updates on progress about routes to the destination, and preference for notifications about whether users are following the system-generated routes or not. Unlike our work, which focuses on NASs that support exploration, Lewis et al. [97] made proposals to *guide* users to a destination instead of giving them the freedom to choose their own routes. Similarly, Scheuerman et al. [129] investigate how VIPs write navigation instructions to each other to better inform the design of turn-by-turn navigation systems. The authors study how VIPs represent distances, indicate directions, and reference landmarks; with an aim to propose design implications for NASs.

Banovic et al. [13] interview both VIPs and O&M trainers to uncover VIPs' information needs for spatial learning. Our work builds on Banovic et al.'s work in two ways. First, we shift our focus from spatial learning to in-situ exploration. In other words, we envision NASs helping users to "figure things out" on their own and make navigation decisions on the fly instead of learning space to visit later on. Second, we investigate the exploration affordances that NASs should offer on a more specific level (RQ1). Banovic et al. found that VIPs desire a "high-level overview" of spaces, while we find in Sections 3.2 and 3.3 that NASs should afford *area shape* information, *layout* information, and assistance in communicating needs with others specifically, as Figure 4.1b illustrates.

Researchers have found that VIPs' navigation strategies are different from sighted people's [140] and that variations in individual VIPs' navigation preferences and behaviors play an important role in designing NASs [3, 155]. For instance, Williams et al. [155] identify personality and scenario attributes that impact VIPs' daily-life navigation preferences. Ahmetovic et al. [3] made proposals for NASs to adapt to the verbosity of navigation instructions to suit users' level of expertise, ensuring that they stay engaged during navigation. As a result, as part of our RQ1 investigation, we also uncover the factors that affect VIPs' choice of spatial information (Section 3.2.2) to identify factors that influence VIPs preferences for spatial information and to understand which specific dimensions of spatial information each of these factors dictate.

Last, prior work has identified many *social* challenges related to navigation that VIPs face as well: specifically, challenges in comprehending assistance from other people [154, 60], in navigating through environments that are predominantly occupied by sighted people [43], and in negotiating these differences with other people [142]. VIPs' ability to explore is best viewed within an interdependence framework [16, 148] — that is, as a collective effort involving other people, as Figure 4.1(b) illustrates. In this spirit, in RQ2 we investigate not only VIPs' internal challenges when trying to explore, but also how VIPs interact with people when trying to explore. Our aim with this latter aspect of RQ2 is to understand how NASs can bridge communication gaps and foster collaboration as yet another means of exploration.

2.4 Ubiquitous Physical Artifacts for Social Connection

Many prior works focus on improving social connection for people in Long Distance Relationships (LDR) or more generally, people who live in separate households. Examples of such systems include household fixtures and furniture such as bathroom mirrors, bed-side drawers, stools [131, 134, 38], and household objects such as stuffed toys, candles, tools, picture frames and desktop toys [49, 64, 37, 25, 87]. Some works created entirely new physical artifacts such as novel desktop toys and radios [22, 69] rather than augmenting existing ones. As pointed out by Li et al. [98], a majority of systems rely on a single type of device for bidirectional communication, meaning they used a symmetric pairing of objects. There are also a few systems that feature non-matching connected objects. Examples of asymmetric systems, include Shared Wind [158], a uni-directional communication system with sender and receiver curtains, and Flex-N-Feel [135], which comprised a flex-sensing sender glove and a vibrotactile receiver glove. A pioneering work, AmbientROOM, mapped [77] a pet's movement is mapped to a visual projection of ripples on the ceiling.

User studies for these systems demonstrated that they were helpful in fostering improved feelings of presence and social connection. However, there is still much more room to investigate how people would use and be impacted by having ubiquitous socially-connected physical artifacts dispersed throughout one's environment. Therefore, with our technology probe, we enable users to designate existing artifacts in their homes as connection endpoints, establish how they are mapped to their remote friends' artifacts, and manage how many concurrent connections they use within their personalized ecosystem of connected artifacts. In this way, we can begin to gather insights in how people behave given the ability to create a ubiquitous constellation of social connections.

2.5 Understanding Technology-Mediated Social Connection

Many previous researchers have explored the design space for technology-mediated social connection. As Hassenzahl et al. [66] explain, the feeling of "relatedness" is an integrated psychological human need that technologies can support by supporting people in *awareness*, *expressivity*, *physicalness*, *gift giving*, *joint action* and *memories*.

Given the wealth of strategies, many efforts have been made not only to create instances of these technological systems but to understand and map out their design space. For instance, many researchers [106, 121, 57] have identified important design dimensions for ambient-media systems, ranging from information capacity and notification levels to sensory mediums, personalization and more. In a systematic review of 150 articles of unconventional user interfaces for LDR emotional communication (i.e. excluding mobile apps) by Li et al. [98], it was found that non-symmetric pairings of devices (meaning that the two objects are not of the same kind) and longer-duration studies of technologies for social connection in real-life use contexts remain underexplored and under-represented. Since we wish to expand knowledge in how a ubiquitous computing approach can be used for social connection, it was particularly necessary for us to incorporate these two aspects as part of our investigation.

We base our investigative approach on a technology probe [74], a research technique well-suited to studying social connections due to its ability to reveal surprising insights. For instance, Lottridge et al. [102] uncovered the power of promoting sharing during "empty moments" to nurture long-distance relationships. In another example, Judge et al. [83, 82] explore video-based platforms for social connection between remote families. They discovered that Family Window [83], which connected two households, triggered routine sharing of everyday moments, but that Family Portals [82], which connected three households, did not trigger such routine sharing. Grivas [59] experimented with establishing an imaginary "merge" of two homes using arrangements of physical LED prototypes in people's homes, and found that incorporating people's spatial knowledge of each other's places could evoke intimacy and a sense of presence. Unlike these previous technology probes, Social Wormholes gives users a high degree of control over how to connect their space with their friend's space (users can connect anything with anything), allowing us to understand how people feel and behave with the ability to configure a ubiquitous computing environment specifically for social connection. Our insights can inform the design of ubiquitous systems for social connection.

Other systems have explored AR as a means of sending and leaving physically-grounded messages for friends and colleagues. Specifically, they explore the paradigm of "leaving behind" AR text [99, 112, 11] and audio messages [92] at places so that others see them there later. Unlike this body of work, our technology probe is centered around an ecosystem of connected physical artifacts rather than virtual AR objects being left behind. Other recent works in AR have explored using AR glasses for communication. For example, ARwand [93] enabled people to compose and send virtual content to be rendered on a remote friend's AR glasses, and for which they can see the friend's reactions. ARcall [139] was a platform for a remote friend to "drop in" to see what a remote friend sees, and to inject an AR asset into their view to be seen via AR glasses. In contrast to these works, our AR-glasses-based technology probe does not involve direct sending of content to a person wearing the glasses, but rather allows people to transmit content anchored to virtually connected physical objects. The probe employs the use of AR to make the marginal cost of establishing new connected artifacts small—just more AR markers (pieces of paper)—giving our participants a chance to live in a large ecosystem of connected objects.

Chapter 3: "I Want to Figure Things Out": Supporting Exploration in Navigation for People with Visual Impairments [80]

Navigating unfamiliar environments is difficult for visually impaired people (VIPs). Navigation assistance systems (NASs) are systems that provide users with real-time feedback about their surroundings and their location within the space to enable interactions for supporting navigation. Most NASs such as NavCog [2] and CaBot [62] help VIPs navigate unfamiliar environments via turn-by-turn navigation: by guiding users with verbal instructions (e.g., “turn left in 2 meters”) [2, 45, 12, 109, 123, 124] or by acting as a metaphorical “guide dog” that users follow [62, 85, 84, 10, 119, 125, 128]. While turn-by-turn navigation is successful at getting users to their destinations, several researchers have argued that it endorses a passive role for users during navigation — by having them simply follow directions from the system — instead of giving users the freedom to explore and understand spaces themselves [35, 96, 75, 40, 39, 108].

Research in cognitive science has found that the ability to explore and to play an active role in navigation is crucial for one’s spatial learning [30, 29], cognitive development and brain health [103, 34, 90], sense of independence [55, 32], and agency in making wayfinding decisions [28, 31]. In fact, Banovic et al. [13] found that VIPs strongly desire the ability to explore unfamiliar environments, with one participant adding that "it would be great, magical [to be able to explore] with no one there." Yet Banovic et al. also found that VIPs hesitate to explore unfamiliar environments without proper assistance due to the challenges that they face when trying to explore them. Together, this research shows two opportunities for future NASs to benefit VIPs: by supporting exploration and spontaneity in navigation, and by helping VIPs overcome challenges in exploring unfamiliar environments so they become confident in doing so.

Here, we aim to establish a holistic understanding of how NASs can be designed to support exploration. Specifically, we seek to discover the information that VIPs need in order to explore unfamiliar environments, as well as understand the challenges that VIPs face when exploring unfamiliar environments. Hence, we investigate the following two research questions:

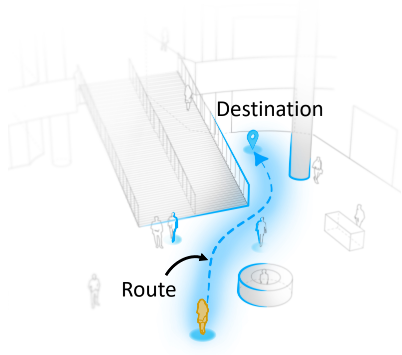
RQ1. What information do VIPs need to explore unfamiliar environments, and what factors influence these needs between individuals?

RQ2. What challenges do VIPs face while exploring unfamiliar environments, both independently and collaboratively?

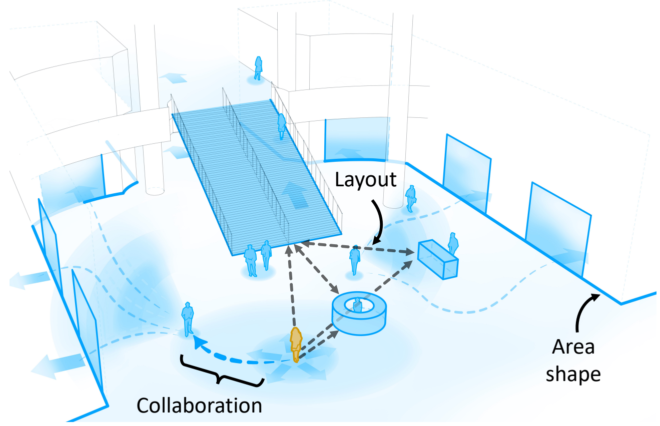
Regarding RQ1, past research has explored how turn-by-turn navigation systems might facilitate exploration by providing additional information about their surroundings [118, 21, 127] and by providing guidance information in a format that enables active engagement [35, 107]. Both Banovic et al.'s findings [13] and findings from cognitive science [68, 101], however, suggest that facilitating exploration requires more than these efforts. Specifically, VIPs desire high-level overviews about their surrounding spaces [13] and can benefit from the ability to form allocentric cognitive maps of spaces (i.e., ones with environment-centered reference frames) rather than egocentric ones [101]. Through RQ1, we seek to discover what the specific form of that high-level information should be and how that might differ depending on individual VIPs' preferences and backgrounds.

Regarding RQ2, a growing body of work prescribes that NASs should not be viewed as merely granting VIPs independence but rather should be viewed as one partner in a collective interdependence effort [16], improving the collaboration between VIPs and others around them. As a result, it is important to understand exploration challenges that arise not only from VIPs' own abilities, but also from failures in how others collaborate with VIPs.

To investigate RQ1 and RQ2, we perform a series of in-depth semi-structured interviews with 12 VIPs and short follow-up interviews with six other people with whom the VIPs often collaborate by employing a recent Critical Incident Technique (CIT) [47]. These six people included orientation and mobility (O&M) trainers, store employees, and leaders of blind-serving organizations. In addition, our research team included two VIP interns who helped us connect with participants,



(a) Turn-by-turn navigation assistance



(b) Exploration assistance

Figure 3.1: Towards exploration in navigation assistance systems (NASs). (a) Most existing NASs support *turn-by-turn navigation* and give visually impaired people (VIPs) a route-focused view of the world. (b) Our findings reveal how NASs can evolve to be instruments for *exploration* as well, allowing VIPs to form more complete cognitive maps. Specifically, NASs can facilitate exploration in both indoor and outdoor environments: by conveying area shapes, by conveying the layout of objects within environments, and by facilitating effective collaboration between users and others who might enable even further exploration.

develop our interview protocol, and interpret the study data.

Through our interviews, we discovered that VIPs need two types of spatial information for exploration — *shape* information and *layout* information — in addition to the information they need for turn-by-turn navigation (i.e., POIs and route information). We also identified three factors that influence individuals' preferences for spatial information: (1) their onset of vision impairments, (2) their inherent sociability, and (3) their O&M proficiency and mobility aid preference. Understanding *how* these factors dictate the format, source, and amount of spatial information VIPs need leads to an inclusive design of future NASs that support VIPs' exploration.

Regarding VIPs' challenges in exploration, we found that VIPs hesitate to explore environments independently because of their lack of confidence in acting upon spatial information collected via non-visual senses (e.g., hearing, touch, smell). Moreover, even when reliable spatial information is available, VIPs still do not feel they can explore environments independently because their self-reported O&M proficiency falls short. When collaboratively exploring environments, both VIPs and their collaborators reported that social pressure on the person helping the VIP is a major obstacle to their successful collaboration. In addition, we found that VIPs' find it difficult to supervise and comprehend assistance from their collaborators.

Figure 3.1 summarizes how our findings can inform the design of future NASs. Figure 3.1a represents the state of NASs today: they are oriented around turn-by-turn navigation and give VIPs a route-focused view of the world, surfacing only those details about VIPs' greater surroundings that are adjacent to VIPs' routes. Figure 3.1b, on the other hand, represents how NASs can evolve to offer exploration assistance as well, leading to a greater formation of cognitive maps. They can facilitate exploration in several ways: by conveying area shapes, by conveying the layout of objects within environments, and by facilitating effective collaboration between users and others who might enable even further exploration. We describe these possibilities in detail in our Discussion section where we identify specific research opportunities, discuss socio-technical challenges, and analyze practical considerations; that can bring us closer to this broader vision for NASs. Finally, we inform future approaches in research within the CSCW community on ethical considerations that may be adopted while engaging with the broader VIP community.

3.1 Empirical Study

We performed a qualitative study guided by our two research questions RQ1 and RQ2. Here we describe our recruitment process, experimental procedure, and data analysis procedure.

3.1.1 Participants

We recruited 12 visually impaired participants (VIPs) — seven men and five women — with a wide range of ages (18 to 72). Table 3.1 summarizes participants' demographics; all participants' names in the table are pseudonyms. Note that we assigned pseudonyms by randomly sampling common names from our participants' geographical locations and racial identities.

Participants identified themselves with diverse racial identities — specifically, as Asians, Black or African Americans, Whites, or Hispanic/Latinos. We collected gender information as a free-response, optional field to ensure inclusiveness of all gender identities. Participants also had diverse visual abilities, onset of vision impairment, and mobility aid preferences. Ten are white cane users and two use guide dogs. All live in the United States, spread across nine different states.

We recruited the VIPs from several sources. First, we posted to online forums and social media platforms popular among the visually impaired community, recruiting six participants in the process. Second, we connected with two participants through our research team's ongoing collaboration with a major blind-serving organization. We recruited the last four participants via snowball sampling [58].

In addition to the VIPs, we recruited six other participants from groups who the VIPs reported as often collaborating with and who play a big part in shaping VIPs' behaviors around navigation. The six others include two leaders of a major blind-serving organization (their assistive technology director and their director of O&M services), a manager of disability services at a large university, an O&M trainer, and two store employees (one working at a small bookstore and the other at a major department store). We selected these two store employees because they self-reported as regularly interacting with visually impaired customers.

Table 3.1: Self-reported demographic information of our visually impaired participants.

Pseudonym	Gender	Age	Onset	Mobility Aid	Nature of Vision Impairment
Harper	F	59	Age 20	Guide dog	Total blindness
Yusuf	M	22	Birth	White cane	No vision in left eye; Shape, color, and movement in right
Anika	F	72	Age 26	Guide dog	Total blindness
Booker	M	25	Age 4	White cane	Total blindness
Daniel	M	21	Birth	White cane	Total blindness
Rahul	M	33	Birth	White cane	Total blindness
Anya	F	19	Birth	White cane	Light perception, shapes, color in left eye; No vision in right
Miguel	M	23	Birth	White cane	Total blindness
Charles	M	25	Age 1	White cane	Light, shape, color, and movement in left eye; No vision in right
Zendaya	F	18	Birth	White cane	Total blindness
Lucas	M	36	Birth	White cane	Total blindness
Olivia	F	21	Birth	White cane	Light perception in left eye; Color, contour, and shadow in right

3.1.2 Procedure

To develop our interview protocol and study procedure, we conducted pilot interviews and brainstorming sessions with two VIPs — working as paid summer research interns as co-authors on another project within our lab — in order to begin understanding VIPs' experiences around exploration. Both VIP interns reported being partially blind (or low vision), and were college students (both males, aged 20 and 21). We invited them to serve as pilot study participants, to review our interview questions, and to discuss participants' responses. Involvement of the two VIP interns helped us in many ways. First, during our pilot interviews with them, they provided us an initial understanding about VIPs' experiences around exploration, helping us refine the interview questions and removing ambiguous language from it. Second, they helped us recruit participants via snowball sampling [58]. Last, being able to consult them for quick clarifications about our understanding of the study data was crucial to the data analysis phase. We reflect on the ethical considerations of involving the two VIP interns in our study in Section 3.4.3.

Our final interview protocol was organized as follows. We began each interview by collecting participants' background information, including their demographics (age, gender, race, location), onset and level of vision impairment, history of O&M practices, mobility aid preference, and use of assistive technologies for navigation. Collecting this background information helped us identify correlations between different individuals' exploration preferences and their past experiences. We then turned to RQ1 and RQ2 by employing a recent Critical Incident Technique (CIT) [47], in which we asked participants to recall and describe a recent time (or *incident*) where they explored an unfamiliar environment. CIT is commonly employed by the HCI and CSCW community for conducting in-depth interviews [73, 86, 115, 156]. We adopted CIT because it gave us actual examples of times when our participants faced challenges in exploring unfamiliar environments, without having to undergo an extensive contextual inquiry and follow participants around all day long. However, as a limitation, future research could shadow VIPs to understand the context of their experiences in more detail and reveal more subtle nuances that may have been overlooked by using CIT.

Between our participants, we learned about many incidents of navigating unfamiliar *indoor* environments (e.g., hotels, grocery stores, airports, train stations, academic buildings at universities) and *outdoor* environments (e.g., sidewalks, street crossings, large open spaces in shopping complexes). Examples of incidents that participants shared include traveling from their hotel rooms to a vending machine or to breakfast, walking around a grocery store to find a specific item which was moved to a different location by management, making their way from a parking lot to a specific department at a university, crossing a busy street by themselves, exploring a shopping complex, and figuring out their way to a recently opened café. Importantly, we noticed that participants tended to explore unfamiliar outdoor environments less frequently than indoor spaces due to them being more concerned about their safety in outdoor settings.

For each recent incident that the participants mentioned, we asked follow-up questions to help them recall how they transpired and to help our team better understand their behaviors during the incident. In general, we led the conversation with questions such as: *"What did you look for when navigating in the space?"*, *"What strategies did you use to gather this information?"*, *"What were the challenges that you faced while doing so?"*, *"What other pieces of information would have helped navigate this environment?"*, *"Were you navigating by yourself?"*, *"Did you consider reaching out for help?"*, *"Who helped you, and how?"*, and *"Which aspect of gathering information did they assist you with?"* Through these discussions, we learned about participants' information needs (RQ1), challenges (RQ2), and workarounds to address their needs and challenges.

During the interviews, we also made special note of people who the VIPs mentioned as often collaborating with and their effect on the VIPs' navigation behaviour. To further investigate RQ2 from the perspective of these other people, we conducted short follow-up interviews with six representative non-VIP participants, described in Section 3.1.1. Soliciting experiences from both VIP and non-VIP perspectives helped us find the root cause of the challenges that VIPs — and in some case these non-VIPs — face when exploring unfamiliar environments collaboratively.

We asked these six others about their backgrounds, their frequency of interactions with VIPs, their role in assisting VIPs in navigation, and their experience with assistive technologies for VIPs (if any). We used the same critical incident technique [47] as before, but we asked these participants to recall and walk us through their past experiences interacting with VIPs, specifically instances in which they helped VIPs with navigation-related tasks.

We conducted all interviews via a Zoom video-conference, except for two: the bookstore employee preferred to be interviewed in person during working hours, and Anika preferred a telephone interview since she was not comfortable using Zoom. All interviews were recorded with participants' consent. Each interview lasted 60–90 minutes and the participants were compensated $25 for their time. We collected over 23 hours of recordings in total. The study was approved by our institution's IRB.

3.1.3 Data Analysis

We analyzed our interview data via a grounded theory approach [26]. Following grounded theory, we simultaneously performed data analysis and collection, iteratively refining our analytic frame while also updating the questions for future interviews as we identified emerging themes. The primary author and a co-author collaboratively performed open coding [138] on the interview transcripts while interviews were still ongoing to arrive at an initial set of codes. We also held brainstorming sessions with the two VIPs on our research team to validate and refine some of these themes. We collaboratively synthesized the initial set of codes and recruited participants for interviews as necessary to arrive at theoretical saturation [138], which we achieved after interviewing

12 participants. Finally, we conducted weekly meetings to review the codes and refine them into a closed set of codes, which we then re-applied to the transcripts to reach a “group consensus” [126].

3.2 Information Needs for Exploration

In this section, we present our findings for RQ1: What information do VIPs need to explore unfamiliar environments, and what factors influence these needs between individuals? Our interviews revealed that VIPs need two types of spatial information (Section 3.2.1) for exploration — shape information and layout information — in addition to the information they need for turn-by-turn navigation (i.e., POIs and route information). We also discovered factors that influence these information needs between individuals (Section 3.2.2). Throughout our results, we highlight key insights that inform the design of future NASs supporting VIPs' exploration in navigation.

3.2.1 Spatial Information

We found that participants want to learn spatial information in a hierarchy — first, the shape information, then the layout information, followed by specific details about the route to a destination. Participants noted that the shape and layout information give them a high-level overview of the environment, allowing them to decide their route to the destination by themselves. Our findings extend prior work [13] by specifying what it means for VIPs to obtain a "high-level" overview of a space.

We note an important difference between what VIPs want during exploration and how current NASs facilitate exploration. While current NASs' approach of announcing nearby POIs [118, 21, 127] promotes a egocentric reference frame, we found that VIPs want to build their cognitive maps in an allocentric reference frame via shape and layout information. Next, we describe the two types of spatial information.

Shape information

Participants described shape information as a skeletal wire-frame of the unfamiliar environment, marking its bounds. Shape information provides VIPs with a high-level overview of the structure of the space very quickly. Many participants (n=4) indicated that shape information forms the basis of their mental map, onto which they append other pieces of information including object layouts and routes. Booker, recollecting his recent visit to an office complex, explained how he would ask for shape information before anything else:

> *"[I ask] ... 'What does this building generally look like?' Because I want to understand its shape. That's one of the first things [I want] to understand."* –Booker

Participants described using shape in context of both indoor and outdoor environments. For indoors, shape is understood to be the boundary or walls of a room and thus, can be represented in the form of geometric shapes such as squares (e.g., offices) or rectangles (e.g., hallways). For outdoors, participants referred to the environment's general dimensions of walkable area as its shape. For instance, Olivia explained how she values information about width of the sidewalk and the streets when the environment may require crossing streets.

Interestingly, we learned that VIPs use shape information differently for turn-by-turn navigation and exploration. Williams et al. [154] found that, for turn-by-turn navigation, VIPs use shape information to orient themselves and walk in straight lines. In contrast, we found that, for exploration, VIPs use shape information to get a sense of the environment's high-level structure.

Layout information

Participants described layout information as the arrangement of different objects within the space — both with respect to them (egocentric) and with respect to the environment (allocentric). The objects constitute several categories including points of interests (POIs) (e.g., stairs, elevators, restrooms), landmarks (e.g., change in flooring, curbs), obstacles, and other people in the environment who the VIPs often see as potential collaborators in exploration.

For example, Yusuf recalled his visit to an unfamiliar grocery store where he first focused on understanding the shape of the store, and then populated this structure with layout information. He explained that he sought to understand the locations of certain POIs such as the bathroom, specific aisles, and the cash register to develop a more comprehensive understanding of the space, enabling him to explore the grocery store. Charles described the layout of a space he recently visited with the help of verbal descriptions from his friend:

> *"... it's two floors, there's a restroom down the hall on the way as soon as you get in, there is a large step up onto the porch. And then there is double doors leading out to the pool. And there's no gate around the pool."* –Charles

We noticed subtle differences in VIPs' use of landmarks and POIs between navigating to a destination and exploring unfamiliar environments. On one hand, participants described using landmarks and POIs either as potential destinations or as locations to reorient themselves along the route; pointed out by prior work [52]. For exploration, on the other hand, participants mentioned using landmarks to create a more comprehensive mental map so that they can make navigation decisions in situ.

> **Insight 1**: VIPs need two types of spatial information: shape information and layout information, to get a high-level overview of a space.

3.2.2 Factors Influencing Information Preferences Between Individuals

We discovered three factors that influence VIPs' preferences for spatial information: (1) their onset of vision impairments, (2) their inherent sociability, and (3) their O&M proficiency and mobility aid preference. Not surprisingly, many of these factors have been observed to affect VIPs' navigation behavior in different contexts [101, 152, 130, 143, 154, 155]. Thus, we identified dimensions of information needs — specifically, spatial information — dictated by these factors in context of exploring unfamiliar environments. VIPs' preferences dictated information needs along three dimensions, (1) preferred format of spatial information: sensory augmentation vs. detailed descriptions, (2) preferred source of spatial information: via other people vs. via self, and (3) amount of support for gathering spatial information: minimal vs. maximal support; respectively.

Onset of vision impairment and preferred ‘format’ of spatial information

We observed differences in VIPs’ preferred *format* for spatial information, which depended on when their onset of vision impairment came about.

Many early-blind participants (n=3) — people who are blind by birth or developed vision impairments early in life — shared that they have learned to trust their non-visual senses to collect spatial information over time. These participants further explained that they prefer receiving *confirmation* of their sensed information either from other people or through their other senses, instead of receiving complete *descriptions*, and that they prefer their non-visual senses to be amplified (e.g., through a more powerful echolocation ability) rather than mutated (e.g., through system-provided labels). These participants noted that doing so helps them maintain their sense of independence, which is important to VIPs as reported by Lee et al. [95].

By contrast, the late-blind participants expressed preference for receiving spatial information in the form of verbal descriptions with as much visual detail as possible. Two of our late-blind participants, Anika and Harper, attributed their preference for descriptions of spatial information to their having had vision in the past, allowing them to visualize spaces.

> *“I have a pretty good running movie of the world and what it looks like around me and a picture of it. [T]his knowledge [of] how things are put together and look like is definitely [an] advantage of having seen for 25 years.”* –Anika

Harper noted that including visual details, such as colors, within verbal descriptions helped her visualize spaces and memorize them. None of the early-blind participants showed interest in learning or referring to visual concepts such as color when receiving spatial information.

Inherent sociability and preferred ‘source’ of spatial information

We found that participants’ preference for seeking assistance from others to collect spatial information — i.e., *collaborative exploration* — is correlated to their inherent sociability and prior experiences of being assisted by others. While all participants described instances of seeking assistance from others, many (n=5) expressed their preference for using other people as a source of spatial information, instead of doing it all by themselves.

For some of these participants it was easier (Miguel) and faster (Lucas) to gather information via others. Many others (n=4) felt independence in seeking help from others, stating that *"independence also has to do with self-advocating for [oneself]"* (Zendaya). Most participants who preferred collaborative exploration shared positive experiences of receiving help, even from strangers, and self-reported as being socially adept.

Interestingly, Anika mentioned that asking for spatial information from others was also a way for her to connect with people. She shared instances of building relationships with several people who help her on a regular basis:

> *" I could do online shopping or delivery shopping with CVS, but I don't want to. These people become my friends. [...] I like going up and connecting with the people."*
> –Anika

Other participants (n=4) expressed their preference for gathering spatial information by themselves — i.e., *independent exploration* — whenever it was possible. For most of these participants, we found that they value their ability to explore independently above everything else, and some expressed discomfort in interacting with other people due to negative experiences of seeking help from others. We heard many stories about people not knowing how to help VIPs, similar to what Williams et al. [154] and Guerreiro et al. [60] have reported.

O&M proficiency/mobility aid preference and preferred 'amount of support'

Participants were split on the amount of support they need to gather spatial information in order to successfully explore unfamiliar environments. These differences were found to be correlated with VIPs' self-reported proficiency in O&M skills (being exposed to limited/no training vs. sufficient training) and their mobility aid preference (guide dog vs. white cane).

Most participants who self-reported as having limited exposure to O&M training (n=3) described wanting a higher degree of support from NASs, i.e., detailed spatial information, compared to those who had a greater exposure to O&M training. In fact, some of the participants with limited O&M exposure reported to be content with turn-by-turn navigation and did not express a strong desire for the ability to explore unfamiliar environments. As a consequence, they found it extremely hard to infer spatial information on their own.

> *"Usually for groceries, I ask somebody to assist me because [...] I feel like the shape of the store is really complicated to learn."* –Miguel

We also observed a similar pattern with mobility aid preference. Both of our participants who use a guide dog — Anika and Harper — exclaimed that it is extremely hard for them to explore environments with the help of a guide dog. Harper explained that exploring environments with a guide dog is more challenging than with a white cane.

> *"That's the real downside for my seeing eye dog. To explore a new space, I am supposed to tell him, give him commands. If I don't know where I'm going, I can't tell him."* –Harper

Insight 2: VIPs' preferred format, source, and amount of spatial information support vary between individuals depending upon their onset of vision impairment, their inherent sociability, and their O&M proficiency and mobility aid preference, respectively.

3.3 Challenges in Exploration

In this section, we present our findings for RQ2: What challenges do VIPs face while exploring unfamiliar environments, both independently and collaboratively? Our analysis revealed several challenges that VIPs face during exploration, which we present around two major means of exploration, (1) *independent exploration*: exploring by themselves (Section 3.3.1), and (2) *collaborative exploration*: exploring by seeking assistance from others (Section 3.3.2).

3.3.1 Challenges in Independent Exploration

We discovered two major challenges in our participants' independent exploration endeavors. First, participants reported difficulties in gathering spatial information precisely and reliably via their non-visual senses (e.g., hearing, touch, smell). Second, participants described challenges in acquiring appropriate O&M training and maintaining their O&M skills. We elaborate upon these challenges in the following sections.

Gathering spatial information precisely and reliably

Interviewees shared many instances in which they gathered spatial information — shape and layout information (see Section 3.2.1) — using their non-visual senses such as hearing, touch, and smell. Not surprisingly, VIPs' use of their non-visual senses for navigation has been reported by prior research as well [143, 13, 155, 154, 142]. Interestingly, though, we found that spatial information gathered through these senses was neither precise nor reliable for VIPs to make in-situ navigation decisions, severely impeding their ability to explore unfamiliar environments independently.

Some participants (n=3) described using their sense of hearing — particularly, echolocation — to gather shape information, but lamented that it only gives them a very rough idea of the environment's shape and lacks the precision to work well in large or crowded places.

Booker recalled visiting a shopping mall, describing how echolocation was not precise enough for him to gather shape information.

> *"... echolocation can tell me some things about the shape, but I want specifics. So, I will go to each side of the entrance and check how big the entrance is, and then I can learn that there are two large openings from this foyer."* – Booker

Although our participants reported trusting their sense of touch over other senses, it was still not a reliable way as the "brute force approach" does not scale well to large spaces (e.g., airports, shopping complexes). Furthermore, participants expressed hesitation in using touch, including tactile feedback via their cane, to gather spatial information when other people are present in the environment. Charles mentioned concerns about hitting people with his cane in crowded places, while Olivia expressed fear of knocking objects over in front of others. Harper echoed the sentiment, stating that using touch might be inappropriate in some public settings.

> *"I mean, if you're somewhere by yourself, you could explore anything. But when you're in a public setting, people are really gonna look at you strangely if you get up at a restaurant and start walking around and feeling all the tables."* –Harper

Approaching this finding from Easley et al.'s [43] perspective — the majority of people occupying an environment dictate its social norms — we could in fact say that VIPs' independent exploration strategies using their non-visual senses is "disruptive in predominantly sighted environments."

Participants mentioned relying the least on their sense of smell for exploration. Many recalled specific examples: such as detecting the smell of fries (Anya), laundry (Zendaya), and garbage (Rahul) to identify certain landmarks, helping them make an educated guess about the possible layout of the space. However, this information is not concrete enough for them to act upon, and is primarily used to supplement other senses.

> *"That's usually not my first priority. [The sense of smell] is more maybe just providing some supplemental information. I would not say that that's something that I rely on in any capacity."* –Rahul

Insight 3: VIPs face difficulties in making navigation decisions based on spatial information collected via their non-visual senses.

Acquiring appropriate O&M training and maintaining O&M skills

We discovered that most participants (n=7) expressed difficulties in exploring environments independently because of lack of confidence in their O&M proficiency. Participants indicated that this was not because O&M techniques are not sufficient to support independent exploration, but rather attributed this hesitation to their lack of access to appropriate O&M training and their inability to maintain O&M skills.

Upon further inquiry, we found three hindrances that prevent VIPs from acquiring adequate O&M training resources: lack of funding, shortage of O&M instructors, and difficulties in setting up O&M sessions as an adult — specifically those who developed vision impairments later in life. Most participants were aware of the power of O&M skills and lamented on the lost opportunities to explore unfamiliar environments by themselves. As Charles exclaimed:

> *"I feel like I would have benefited [with more O&M training]. I don't want to feel like I'm over exaggerating, but at least 10 times more."* –Charles

Few participants (n=3) reported receiving appropriate O&M training, yet still did not feel confident in exploring environments independently. Participants noted that this was because of their inability to regularly use their O&M skills safely, and thus were concerned about atrophy of their skills. Booker elaborated how he denies assistance out of fear of his skills deteriorating if he relies too much on others.

> *"It is very easy to let your [O&M] skills atrophy as a blind person if you rely overly on sighted people[.] It's easy to [use a] sighted guide and become complacent and [not pay attention to] what turns you have taken and where you are in relation to other things."* –Booker

However, he mentioned eventually relying on sighted guide assistance — especially when exploring unfamiliar environments.

> **Insight 4:** VIPs face difficulties in acquiring appropriate O&M training and maintaining their O&M skills, negatively impacting their confidence to explore independently.

3.3.2 Challenges in Collaborative Exploration

We discovered two major challenges that VIPs face when exploring unfamiliar environments by seeking assistance from other people. First, our VIP participants (n=4) expressed concerns about putting social pressure on others while seeking assistance from them. Second, many VIPs (n=5) described difficulties in supervising assistance from others, which is important to their sense of independence. We elaborate on these challenges in the following sections.

Social pressures in collaborative exploration

Participants cited instances where they felt uncomfortable receiving help from others, due to social pressure that the person helping them may face. Booker expressed frustrations about having to put her younger sister in a position where others feel that she is responsible for Booker's actions. He recalled going for shopping with his sister:

> *"I know that my sister gets looks from people all the time, because of foolish assumptions they make out of ignorance. [People think] that she is my caretaker [and that] anything that they perceive as her not doing her job, is wrong."* –Booker

Many participants (n=4) indicated that they are most comfortable seeking assistance from O&M instructors since they are trained professionals and somewhat immune to these social pressures. However, relying on O&M instructors is not always possible, as we discussed earlier (Section 3.3.1).

During our interviews, most VIPs (n=10) recalled examples of grocery stores as an example setting for collaborative exploration. Participants described several different techniques for buying groceries. Daniel, for instance, stated that he calls the store ahead of time to arrange for a personal shopper. Despite the advance notice for assistance, Daniel describes sensing some discomfort when exploring the store with the store employee. To better understand this discomfort and to confirm Daniel's inkling, we followed up with a grocery store employee.

We found that the employees indeed feel the social anxiety, confirming Daniel's claim. The grocery store employee noted that despite his intention to help visually impaired customers, he is *"... always concerned with invading somebody's personal space or [disregarding] their bodily autonomy."* He also mentioned worrying about the company policies and feared getting in trouble if he makes a mistake.

> *"[My manager] said that if you need to help a customer [...] who's disabled, definitely try to if they give you consent [...] Just be careful in that case. But if they don't say anything, then you shouldn't do anything. Because you don't want to actually [cause] issues where they say, 'oh, why are you touching me'?"* –Grocery store employee

We discovered that social pressures affect both VIPs and others, negatively impacting the frequency and quality of assistance that VIPs receive when exploring environment collaboratively.

> **Insight 5**: Social pressures pose a major challenge to VIPs receiving help and to non-VIPs providing help when exploring environments collaboratively.

Supervising assistance for collaborative exploration

Many participants (n=4) described wanting a loose form of collaboration, specifically verbal assistance, when exploring unfamiliar environments with the help of others. Verbal assistance comprises primarily of descriptions for shape and layout information, which enables them to *"figure things out"* by themselves (Zendaya). By contrast, Williams et al. [154] found that VIPs prefer "sighted guide" assistance when walking with another person. This difference highlights that for VIPs, exploration is a self-driven activity and other people play a secondary role in this collaboration. Our participants described challenges in communicating preference for verbal assistance.

In addition, participants mentioned challenges in comprehending verbal assistance. In situations where VIPs do get verbal assistance, they noted that the information they received was often not useful. We found that participants struggle to comprehend spatial information received from non-VIPs because of non-VIPs' predominantly visual descriptions.

> *"[I need to ask for clarification] because a lot of people describe [shapes with letters] like 'U' shaped or 'H' shaped. ... I just prefer geometric shapes [for descriptions.]"* –Booker

While several studies have noted that VIPs' perceptions of space is different from those of sighted people [154, 142], we identified VIPs' preferred format for spatial information — geometric shape descriptions — to inform NAS design.

Interestingly, we found that for this reason many participants (n=3) collaborate with other VIPs who have already been to a location. Zendaya recounted calling her friend, who is also visually impaired, to ask for verbal assistance. Through her friend she obtained spatial information in a more useful format, along with additional cues for her non-visual senses.

> *"So for example, my friend will tell me this train [...] doesn't talk. And I'm really gonna have to pay attention and count the stops."* – Zendaya

Another successful instance of such a collaboration is using remote sighted assistance such as AIRA [7]. Although participants are content with verbal descriptions provided by AIRA professionals, many participants (n=5) noted that it is too expensive for them.

Insight 6: VIPs want verbal assistance in a comprehensible format when exploring collaboratively but find it challenging to communicate this preference to others.

3.4 Discussion

Based on our finding's key insights (Insights 1–6), we present design implications for NASs that can assist VIPs in exploring unfamiliar environments (Section 3.4.1). We hope that these design implications can serve as a catalyst for future research in realizing such NASs. Additionally, in Section 3.4.2, we elaborate on how best to balance turn-by-turn navigation with exploration-based navigation. Specifically, we discuss the interplay between these two forms of navigation and describe an opportunity for accessibility research to focus on *how* users accomplish tasks and not simply *whether* they can accomplish tasks. Lastly, we reflect upon our study procedure with an aim to inform the CSCW community on ethical considerations that may be adopted by future research (Section 3.4.3).

3.4.1 Design Implications for NASs

Table 3.2 summarizes key insights from our findings and design implications for developing future NASs. The interviews helped us identify key insights about VIPs' information needs, factors that affect these information needs, and challenges that VIPs face that impede their ability to explore unfamiliar environments. In the following sections, we describe how NASs can be designed to support these information needs and alleviate these challenges.

Facilitating active engagement and supporting individual variations

Our findings reveal that VIPs need two types of spatial information — shape information and layout information — in order to obtain a high-level overview of a space (Insight 1). Participants described wanting to acquire this spatial information before anything else (Section 3.2.1), and recent research [33, 107, 111] has shown that VIPs should be able to gather this information via interactions that foster active engagement. Our findings also reveal the importance of allowing VIPs to customize the format, source, and amount of spatial information support they receive to suit their background (Insight 2).

Collectively, these insights can influence NAS design in exciting new ways. In Figure 3.2, we show a conceptual illustration of how a future NAS might help users gather spatial information in an indoor environment while facilitating both active engagement and customization. We note that the illustration we propose is one of the many possibilities in the design space of building such NASs. Through this example, we aim to kick-start discussions around socio-technical challenges and practical considerations that the research community would need to address before realizing NASs that support exploration (more on this in Section 3.4.1).

To support exploration, we conceptualize a wearable sensor such as LiDAR or a depth camera that scans for shape information by recognizing different elements of the environment including corners, straight edges, and curved edges. The sensor also scans for layout information by detecting objects such as doors, stairs, and elevators. The NAS conveys this information to the user via speech or sonified waveforms depending on the user's preference — recall from Section 3.2.2 that early-blind VIPs prefer amplifying their ability to hear while late-blind VIPs prefer spoken descriptions. Users receive this feedback on-demand, perhaps by "looking around" via a NavStick-like interface [111], since continuously "pushed" feedback can impair VIPs' ability to hear safety-critical sounds [13, 154, 43]. We can imagine a similar system being used in outdoor environments, detecting sidewalks, crosswalks, pavements, and the shape of walkable area within the space.

Beyond wearable sensor-based NASs, navigation tools such as tactile maps have potential to help VIPs gather shape and layout information from an allocentric reference [44, 19, 147, 1, 79, 141, 78, 110]. However, in order to render graphics on tactile maps, information about the floor plan (indoors) or street view maps (outdoors) is required, which may not always be available for unfamiliar environments. Combining wearable sensors with tactile maps provides opportunity to support VIPs' exploration by sensing VIPs' immediate environment and rendering it via tactile maps in real-time. Recent advancements in commodity tactile displays such as the Dot Pad [41], would further allow researchers to develop tools that may support different use cases using the same device. Although sensing systems that use braille displays are not uncommon [150], they mostly provide route-based knowledge such as obstacles and landmarks. Re-purposing existing tools and systems to support exploration is an open area for research with its own challenges. Dey et al.'s work [40, 39] on designing map-based interfaces that support exploration for sighted people provides a good starting point for future research.

Challenges and considerations in supporting exploration via NASs

While our work introduces several ideas for how NASs can support VIPs' exploration, future researchers must still solve technical challenges, be cognizant of practical considerations, and address social considerations before such systems can make a real impact in VIPs' lives. We discuss these challenges in context of the wearable sensor-based NAS illustrated in Figure 3.2.

Research in robot navigation and computer vision has made significant progress in perceiving the environment using navigation stacks [62] and deep learning models [100, 15]. However, systems for supporting exploration such as the concept expressed in Figure 3.2 require further research and development. Technical challenges may be caused by several things: (1) occluding objects or other people within the space: making it hard to perceive the actual shape of the environment, (2) finite range of sensors: limiting applicability of such systems to large open spaces such as shopping malls, and (3) camera instability of on-body sensors: causing blur and severely affecting the accuracy of vision algorithms as the user walks around.

In addition to the technical challenges, NAS designers would need to address several practical considerations. To begin with, NASs should not be cost-prohibitive for VIPs, who have been found to earn 30–40% less than sighted people [89, 20, 50]. Low-cost sensing methods such as pure camera-based systems, however, are typically much less accurate than systems such as LiDARs. It will be important for researchers to develop calibration and error-recovery mechanisms to counter the limited capabilities of low-cost equipment. Yoon et al.'s smartphone-based NAS [157], for example, requires users to initialize it by orienting the phone horizontally to face the ground, always at the same location at the beginning of a session.

We also found that VIPs do not want to "stand out" while navigating unfamiliar environments, wanting a more discreet form factor for the wearable sensor such as that depicted in Figure 3.2. Interestingly, this finding contradicts Lee et al.'s recommendation that NASs should be visible to other people within the environment, in order to assuage their privacy concerns. Future approaches should further explore this contradiction and begin to find ways for managing the trade-off.

One solution may be to create awareness within the sighted community about common assistive technology devices. K-12 schools could, perhaps, include lessons on accessibility by discussing VIPs' general practices and the use of assistive technology to instill acceptance and awareness. Another solution could be introducing new security mechanisms within NASs to further ease this conflict. For instance, NASs such as that depicted in Figure 3.2 often send data over cloud for complex computations of computer vision algorithms. To prevent leakage of any private information, future NASs could perform the initial feature extraction on-device, before any data is sent over the network for processing. This would reduce the risk of data leakage over the network.

Precision and reliability afford in-situ exploration

From our interviews, we learned that VIPs hesitate in acting upon information collected through their non-visual senses such as hearing, touch, and smell (Insight 3). For example, both Charles and James expressed concerns about making navigation decisions based on the rough estimate of an area's shape that they gathered via echolocation. Hence, NASs should provide precise and reliable spatial information about environments to VIPs. Just as turn-by-turn navigation efforts have spurred research on accurately locating users and providing them with precise turn-by-turn instructions [109, 6, 2], the cause of facilitating exploration assistance will require research on accurately sensing environments' shapes and layouts and providing this information to users in a precise manner.

In addition, future NASs may have to perform post-hoc interventions to compensate for impreciseness that may arise in VIPs' perception of their surroundings. For instance, a slight imprecision in VIPs' sense of orientation could lead to rotationally inconsistent cognitive maps of the space, causing VIPs to make incorrect navigation decisions. As an example, in Figure 3.3 we illustrate

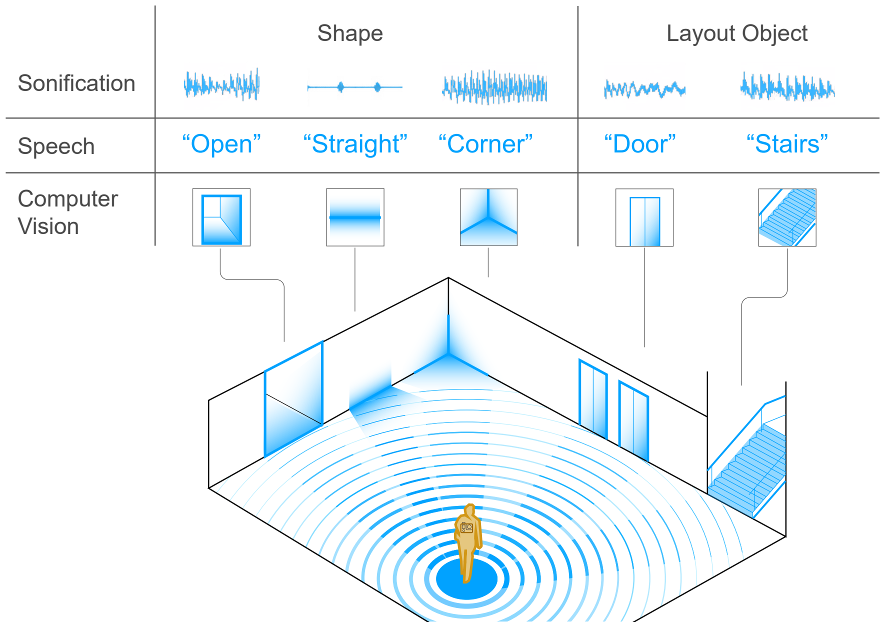


Figure 3.2: Conceptual illustration of a NAS facilitating spatial information in an indoor environment. The NAS consists of a wearable sensor that detects the environment's *shape* and *layout* using computer vision. Users can actively explore by "probing" the environment on demand and can choose a preferred format for the information: either sonified waveforms or speech. We found that early-blind and late-blind users respectively prefer these two formats. Similarly, we can extend this concept to facilitate spatial information in outdoor environments as well. We can imagine a similar system being used in outdoor environments that detect sidewalks, crosswalks, pavements, and the shape of walkable area within the space.

how a minor error in VIP's perceived orientation could lead them to misjudge the walkable area within an outdoor environment, a crosswalk in this case, and potentially end up in a dangerous situation. Many researchers have recently focused on mitigating user errors such as veering [117, 81, 104] and over-turns [5, 4] because of their affect on how well turn-by-turn navigation assistance systems perform. Analogously, we can imagine further research into identifying and resolving user errors that arise during in-situ exploration assistance.

O&M education assistance as a means of empowering VIPs to explore

From our interviews, we learned that VIPs lack confidence in their O&M skills — due to either their lack of appropriate O&M training or lack of opportunities to maintain their skills — which leads many VIPs to become wary of exploring new places even if they may want to. Participants

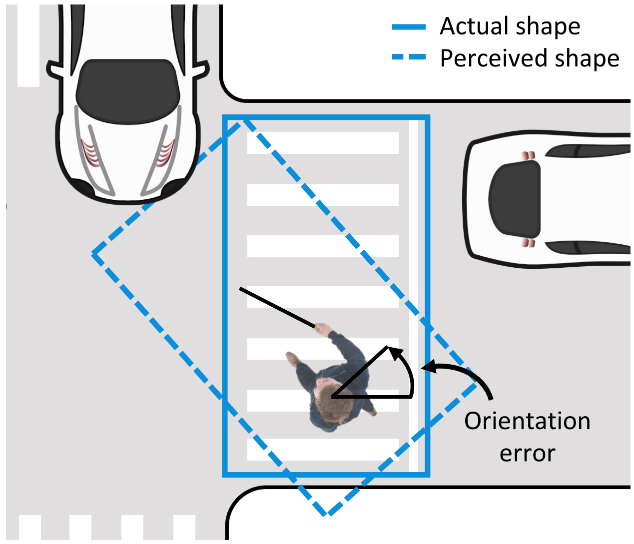


Figure 3.3: Illustration of a rotationally inconsistent cognitive map in an outdoor environment. Here, a VIP's imprecise sense of orientation leads to them incorrectly understanding how a crosswalk is situated. This may lead them in the path of a moving car unless they course-correct using the tactile information gathered via their white cane or the sound of the cars and other pedestrians. Future NASs may need to identify and resolve these types of user errors during in-situ exploration.

agreed that having appropriate O&M training and opportunities to practice their O&M skills regularly would enable them to independently explore. In short, O&M skills are a powerful enabler for exploration.

As a result, immense opportunities arise for NASs to be designed in a way that promotes O&M education as users navigate, empowering VIPs to become confident in exploring environments. In other words, future NASs can include built-in O&M education facilities to give VIPs access to O&M instruction and support without requiring human instructors, which we found in Section 3.3.1) to be in very short supply. Very recently, Harriman et al. [65] introduced Clew3D, a smartphone application that uses LIDAR to automatically generate O&M instructions for a route, identifying O&M landmarks such as open areas, walls that can be shorelined, and doors as part of the instructions. This work takes an exciting step toward incorporating O&M training into NASs, but it is turn-by-turn-focused and does not explore facilities for O&M teaching or practice.

Future NASs can further incorporate O&M education by offering O&M training modules and posing O&M training "challenges" or "problem sets" over the course of the day if users want them, doing so in a similar manner to education and workout apps. The NASs can craft these challenges for the user based on the systems' own understanding of the environments' shape and layout. They should be careful, however, not to push users into taking up tasks they do not wish to practice or perform — users should be in control of when and how they would like to learn. O&M instructors themselves can also be part of the loop — one can imagine an NAS that keeps detailed system logs of a user's O&M performance while navigating and then forwarding the logs to an O&M trainer for review. The O&M trainer might use these logs to identify O&M techniques that the user should practice more.

Mitigating social pressures by standardizing assistance for exploration

VIPs' navigation success is known to be affected by both internal and external factors [155]. Our findings (Insight 5) reveal that social pressures often arise when other people are present and when others may perceive both the VIP and any people helping the VIP negatively. These social pressures can dramatically hurt VIPs' ability to receive help and collaboratively explore. Moreover, our follow-up interviews with relevant non-VIPs revealed that even people helping VIPs feel social anxiety about how VIPs and onlookers perceive their ability to help. VIPs are aware of this effect on people helping them and avoid putting them in that position.

Part of this problem, as we learned from Harper's example of people looking at VIPs strangely if they were to get up at a restaurant and start feeling all of the tables (Section 3.3.1), is that it is currently much less socially acceptable for VIPs to explore and receive exploration assistance from others than it is for VIPs to be guided and receive "sighted guide" help from others. Future work can mitigate this problem in two ways. First, NASs with exploration capabilities can enable VIPs to explore environments' shapes and layouts in a much more private way, perhaps through use of a smartphone app rather than having to physically touch objects.

Second, future efforts and advocacy can work to normalize exploration behaviors and establish social norms for exploration that are analogous to the sighted guide technique. To create awareness about these new standards for exploration, we should leverage social media and internet like many disability activists. Future efforts can also promote awareness and empathy by building upon prior work on emulation software [48, 63] that can simulate how people with disabilities "see" or "feel."

Facilitating effective collaboration to enable further exploration

Our interviews revealed that collaboration is a powerful enabler of exploration for VIPs and that VIPs' ability to collaborate effectively with other people (including other VIPs) can help them explore unfamiliar environments further. Participants noted two issues in collaborating effectively with others: issues with communicating their preference for verbal assistance and issues with comprehending others' verbal assistance (Insight 6). As a result, two opportunities emerge for exploring how NASs can bridge communication between VIPs and others to unlock the potential that collaboration can yield.

First, future NASs might help scaffold and facilitate the process of requesting assistance from others, allowing VIPs to specify what information they need as well as what format they need this information. Researchers can explore how NASs might issue structured requests for exploration assistance to nearby people when VIPs ask for it. Second, with respect to comprehending verbal assistance, future NASs might employ natural language processing (NLP) to translate verbal assistance from others to VIPs' preferred format. In Section 3.3.2, we found a mismatch between the languages that VIPs and others use during collaboration.

Of course, important ethical concerns arise from people responding to requests from an NAS rather than a person right next to them. Perhaps, NASs should play a role similar to remote sighted assistance systems such as AIRA [7], which our participants complained as being cost-prohibitive to them (Section 3.3.2). Instead of experts answering VIPs' questions, future research may explore how NASs could do the same to save costs and remove barriers to access. Researchers could collect data from conversations between AIRA agents and VIPs to feed as training data into the NLP algorithm and could investigate the real-life performance enabled by such training. More research can explore how AIRA agents and other VIPs can be kept in the loop to moderate translations in real time.

3.4.2 Balancing Exploration Assistance with Turn-by-Turn Guidance

From our interviews, we discovered that VIPs *"want to figure things out"* (Nora) themselves and desire the ability to explore unfamiliar environments in-situ. While all participants appreciated this ability, some (n=3) did not express a strong preference for having it. These participants indicated their satisfaction with being guided via turn-by-turn instructions, explaining that it was all they needed for their daily-life activities, reinforcing the importance of prior work that builds from this perspective [2, 45, 12, 109, 123, 124, 62, 85, 84, 10, 119, 125, 128].

In fact, even participants who wish to actively explore environments shared specific instances in which they did not mind being guided to a destination. Lucas and William, for example, preferred to be guided at airports when time and convenience were of essence to them. We also observe a clear overlap between VIPs' information needs for exploration and for turn-by-turn navigation. As discussed in Section 3.2.1, VIPs described wanting spatial information — information needed for exploration — *in addition* to route-based information, which is needed for turn-by-turn navigation.

Since VIPs expressed a desire to explore environments in some situations and be guided in a turn-by-turn fashion in other situations, we foresee future NASs facilitating both forms of navigation. However, several questions still remain unanswered. How exactly should NASs combine the two forms of navigation? When do VIPs want to explore and when do they want turn-by-turn instructions? Which agent — the user or the NAS — should initiate the switch between the two forms of navigation, and what factors might NASs use to determine the level of initiative [72] they should take in a given situation? While extensive research is needed to comprehensively answer these questions, our findings on VIPs' exploration preferences and the prior body of research in turn-by-turn navigation can serve as starting points for future investigations.

Ultimately, the significance of exploration and users' sense of agency highlights the importance of framing navigation assistance and other assistive technologies as not just tools but as *experiences* for users. Assistive technology research for a range of populations can benefit from focusing on users' experience while using the system in addition to what functionality the system can help users accomplish. This means that evaluations should weigh both functionalities (i.e., whether users can complete the task) and experience (i.e., how users' actual roles compare to the role they want to play).

3.4.3 Ethical Reflections of Our Study Procedure

In line with recent trends in accessibility research [94, 27, 157, 36, 136, 16], we found it crucial that VIPs are represented in research not only as study participants but also as co-interpreters of the data. In fact, for certain parts of our data, we found it helpful to consult with the VIP interns (involved in the capacity of co-authors on another project within our lab) for quick clarifications and sanity checks on our understanding of the study data. Through this process of including VIPs in the interpretation process, we discovered that the insights and clarifications from the VIP interns stemmed from not just their own lived experiences [120], but also from the experiences of their VIP friends. For instance, one of our low-vision VIP interns often cited the experiences of their totally blind friend during our conversations. Future research approaches should consider including representative users for interpreting study data, especially for research in accessibility.

Additionally, we note that using CIT [47] during the interviews leads to a discussion around actual examples of participants' past experiences, which sometimes may include private identifiable information such as locations of places participants visit, names of their friends and family members. Although we separated participants' names and contact information from their study data, some private identifiable information may have, unintentionally, been stored as part of the interview transcripts. To maintain confidentiality, we redacted all such private information while reviewing the transcripts. Future approaches using CIT should consider reviewing the study data to ensure confidentiality.

Table 3.2: Summary of our study findings in terms of Insights 1–6 and design implications for NASs that incorporate exploration assistance.

Theme	Insight	Design Implication
Information needs	**I1:** VIPs need two types of spatial information: shape information and layout information, to get a high-level overview of a space.	NASs should help VIPs gather shape and layout information in a manner that facilitates active engagement with the environment.
Factors influencing information needs	**I2:** VIPs' preferred format, source, and amount of spatial information support vary between individuals depending upon their onset of vision impairment, their inherent sociability, and their O&M proficiency and mobility aid preference, respectively.	NASs should collect spatial information in a manner that allows VIPs to customize its display along the three dimensions of format, source, and amount of spatial information support.
Independent exploration	**I3:** VIPs face difficulties in making navigation decisions based on spatial information collected via their non-visual senses.	NASs should afford VIPs precise and reliable spatial information and should ensure that VIPs make accurate navigation decisions based on this information.
	I4: VIPs face difficulties in acquiring appropriate O&M training and maintaining their O&M skills, negatively impacting their confidence to explore independently.	NASs can serve as an O&M education assistance tool to give VIPs the confidence to explore unfamiliar environments independently.
Collaborative exploration	**I5:** Social pressures pose a major challenge to VIPs receiving help and to non-VIPs providing help when exploring environments collaboratively.	NASs should normalize VIPs' exploration behaviors by introducing social norms for exploration assistance.
	I6: VIPs want verbal assistance in a comprehensible format when exploring collaboratively but find it challenging to communicate this preference to others.	NASs should scaffold and facilitate collaborative exploration by distributing requests for collaboration and performing translations when needed.

Chapter 4: Social Wormholes: Exploring Preferences and Opportunities for Distributed and Physically-Grounded Social Connections

Family and friends often desire to stay connected with each other over distance. Currently, our way of staying connected with others is device-centric, using smartphones, tablets, and computers. With the onset of smart homes, smart materials, and smart cities, however, the field of computing is slowly marching toward the vision of ubiquitous computing [151], in which technology will evolve to become much more interwoven into our surrounding environment. A major opportunity for ubiquitous computing is to promote staying connected with others in an environment-centered way, repurposing the surrounding environment to serve as connection points with family and friends. Very little work, however, has explored how ubiquitous computing and a potentially large ecosystem of connected endpoints might foster this sort of social connection.

A significant stream of work exploring social connection endpoints is that of *Tangible Bits* [76], *Ambient Media*, *Ambient Telepresence*, and the idea that having connected objects or virtually connected spaces can be a powerful means of feeling close or even together with family and friends over distance. In these works, presence and activity information is embodied in physical artifacts including objects, surfaces, and spaces. For example, in AmbientROOM [77], information about a loved one's activities is relayed via the movement of a computer mouse and the projection of water ripples on the ceiling. Since then, numerous other systems have emerged that have been shown to be effective in supporting a sense of presence, awareness, and social connection in work and domestic life. These have taken on multiple forms, ranging from small household objects like candles, picture frames and desktop toys [25, 22, 87, 64] to augmented furniture [38, 134], and have evolved to relay various types of information, including mood, presence, and activity between people [66].

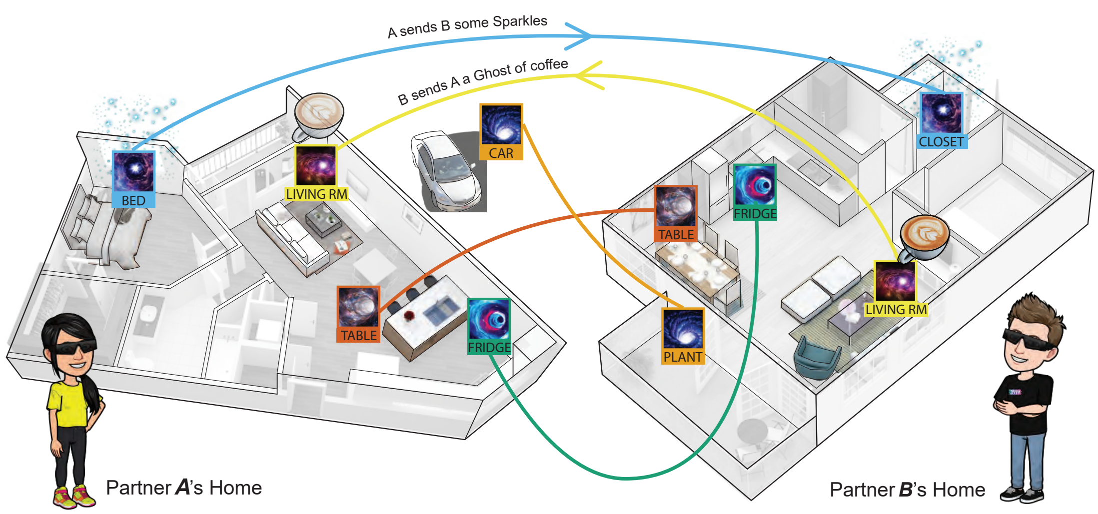


Figure 4.1: Illustration of the *Social Wormholes* technology probe for fostering social connection, which uses physically-grounded connections and transmissions. The connections between two partners A and B are indicated by lines. The system supports symmetrical connections, such as table-table (red), fridge-fridge (green), and living room-living room (yellow). Asymmetrical connections are also supported, such as bed-closet (blue) and car-plant (orange). Partner A looks at her bed wormhole (left) through their AR glasses, which sends sparkles for Partner B to look at later when he visits his closet (right). Partner B captures the coffee mug in his living room (right) and transmits it as a Ghost to Partner A's living room (left).

The vast array of design combinations is indicative that people may have a broad spectrum of needs and preferences for how to connect with one another via more ubiquitous social connections. Prior work echoes this sentiment, suggesting that "one-size-fits-all solutions do not work" for sharing aspects of domestic life [114] and that people develop unique meanings when using augmented objects [8, 66]. What we notice, however, is that existing social connection systems are often designed for use in a fixed configuration, with few options for customization once they have been deployed. Many, for example, are based on a fixed pair of augmented objects with a dedicated set of specialized multi-modal capabilities. As such, user studies with these systems can reveal the impact of those particular designs on social connection, but cannot lead to insights into user preferences beyond the scope of their specific design configurations. Additionally, while technology is maturing to a state where it might be possible to create a landscape of multiple connected artifacts, little is known about how users would perceive and use a broader ecosystem of distributed and physically grounded artifacts for social connection.

Therefore, we take a step back to explore what people's behaviors and resulting preferences would be if given the power to create their own ecosystems of connected objects for social connection. To do so, we create a customizable and scalable *technology probe* [74] called ***Social Wormholes*** and deploy it in a field study with 12 pairs of friends (24 participants) over two weeks. Figure 4.1 illustrates *Social Wormholes*. To make *Social Wormholes* customizable and extensible for our investigation, we base its implementation on augmented reality (AR). With the platform, each person can make various physical artifacts in their homes points of social connection to their respective friend, by attaching printed AR markers. The markers are analogous to the concept of Tabs in Mark Weiser's original envisionment of ubiquitous computing [151], turning any object into a social connection point quickly and cheaply. With the use of AR glasses and dedicated apps, connections can be established between the markers, and the artifacts can serve as mediums through which the friends send and receive snippets of information to each other.

The flexibility of the probe makes it such that a pair of friends may (1) customize which objects in their homes become connected objects, (2) determine how these artifacts are mapped to one another, and (3) elect how many concurrent connections they use with their remote friend in the given period of time. Using this approach, we allow patterns of behavior to organically emerge and capture this through a system of surveys, system logs, and interviews. Based on an analysis, we report a spectrum of user preferences toward social connection. Furthermore, we outline a set of design recommendations for system features that may help to best serve these different populations. In summary, we contribute the following:

1. The design and implementation of an AR-based technology probe of a distributed and physically-grounded social connection system for use between a pair of remote friends;

2. Insights from a field study with 12 pairs of friends (24 participants) on what types of physical artifacts people favor for social connection, how they could be mapped to one another, their perceptions around having a flexible number of connected artifacts, and different scenarios that can be supported with this infrastructure;

3. An outline of different patterns of behavior users exhibit towards physically-grounded social connections, and associated design implications.

4.1 Technology Probe

Social Wormholes is an AR-glasses based system that serves as a flexible platform for social connection between two people. It has three components as seen in Figure 4.2: (1) a set of printed markers (i.e. wormhole images) that users can attach to objects or locations of their choice and distribute within their physical space; (2) a setup app for users to establish new wormhole connections or manage existing connections; and (3) the main AR-glasses application for users to send and receive Sparkles and Ghosts.

We chose to design and build the system using AR glasses for several reasons. First, AR glasses enable scalability. Rather than needing to build multiple specialized hardware objects or installations, any object can be augmented using the glasses. Therefore, a single device can be used to create multiple endpoints at a relatively low cost. Second, AR glasses can enable private viewing experiences. Compared to a physical hardware installation or a smart home display from which anyone in its vicinity can perceive its output, AR glasses can restrict that outputs are only seen by the wearer. Last, in the future when users own their own AR glasses, it could be possible for them to personalize specific aspects of the user experience, for instance, by changing the color or duration of certain effects.

Figure 4.2: *Social Wormholes* comprises three components, from left to right: a set of printed markers that serve as endpoints for connections, a setup app for establishing connections between endpoints, and a connection app to receive and transmit content. Each person in a pair must have access to all components to use the system.

4.1.1 Design and Implementation

We printed wormhole marker images at a size of 8×8 inches on standard letter-sized sheets of paper. We tested the markers under various lighting conditions and viewing angles, and shipped five markers to each participant in order to ensure marker tracking accuracy and robustness.

We developed two apps for our technology probe. First, we built a phone-based setup app (see Figure 4.4). Users can establish up to five one-to-one connections between wormholes of their choice. They can remove and change wormhole connections and setups by editing the connections in the app. In addition, we built a connection app on AR glasses (see Figure 4.3). With the connection app, users can transmit and receive content between the one-to-one wormhole connections they created. While other connection types may be valuable (i.e. one-to-many, many-to-many), we used this as a starting point to keep things simple for users (it is a common mapping pattern for prior systems, as noted in Section **??**). We developed both applications as Snap lenses using Lens Studio[1]. The Social Wormholes system can operate on an iPhone 8 or later and on Snap Next Generation Spectacles. As part of the study, we lent AR glasses to the participants and confirmed that they would have access to a compatible smartphone. The setup app connects to the AR glasses via Bluetooth.

Our system enables two formats of transmissions, *Sparkles* and *Ghosts* As can be seen in Figure 4.3. *Sparkles* are meant to be a lightweight form of communication. A user transmits Sparkles to a friend by simply looking at a wormhole while wearing the AR glasses. Once the gaze is registered, Sparkles are transmitted to the friend's corresponding wormhole. The next time the remote friend passes by their corresponding wormhole endpoint, they can receive the Sparkles by simply gazing at the wormhole marker while wearing their AR glasses. Once their gaze is recognized by their AR glasses, it plays an animation that shows the Sparkles in the form of particle bursts hovering above the wormhole opening on their end. Sparkles can act as an indicator that their remote friend is near their corresponding wormhole endpoint of a particular wormhole connection. *Ghosts* are a higher-fidelity form of communication that sends not just a single bit of information (as Sparkles do) but

[1]https://lensstudio.snapchat.com/

some richer context about the user's surrounding environment as well. A Ghost consists of the image of an object in the user's field of view accompanied by a short five-second audio recording. To begin capturing a Ghost, the user must look at a wormhole and perform a single-finger swipe-forward gesture on the touchpad of the AR glasses. This starts a five-second countdown, during which the surrounding audio is recorded (e.g., ambient noises, speech). At the end of the five seconds, an object in the user's field of view is captured using the forward-facing camera of the AR glasses. The captured object, along with the audio recording, is then sent to the friend's corresponding wormhole endpoint. The Ghost (captured object + audio recording will appear for the friend the next time they look at their corresponding wormhole. This sequence is pictured in Figure 4.3.

In order to facilitate the exchange of information between two connected users in a pair, we also implemented two cloud databases on Amazon Web Services (AWS) to store and read out Sparkles and Ghosts contents that users create. Specifically, we used DynamoDB to store wormhole endpoints connections, users, Sparkles and Ghosts transmission data, and S3 to store content like Ghosts images and audio recordings. Both our phone app and AR glasses app communicate with the two databases to establish connections and support information exchange. Therefore, users needed a secure WiFi connection to use the system.

4.1.2 Setup of Wormhole endpoints

To explore the design aspect of location for a physically-grounded connection system, we designed *Social Wormholes* to enable users to create an ecosystem of connected artifacts and configure the physical locations for their connection endpoints, as shown in Figure **??**. To create a wormhole connection, a user in a pair must first place the printed markers onto an artifact of their choice in their physical space. The user then initiates a connection in the setup app by taking a photo of their marker, and providing a text label to describe the connected artifact. Once saved, the incomplete connection will appear in a list to both partners in the app. The remote partner must then complete the connection in the setup app, by choosing the corresponding side of the incom-

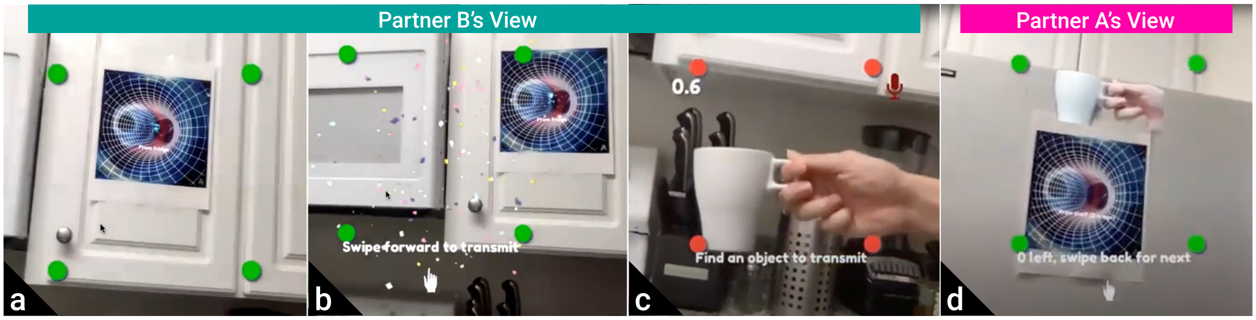


Figure 4.3: Experiences as seen through AR glasses by connected partners A and B. From left to right: (a) B's AR glasses successfully detect the wormhole in his view, as indicated by the four green dots. Upon detection, B sees light blue Sparkles being emitted from his shelf wormhole endpoint, which indicates that A had previously gazed at her corresponding connected endpoint. (b) B's gaze toward his wormhole triggers Sparkles to be sent to A. (c) B decides to send A a Ghost, performing a swipe-forward gesture to initiate the process. A five-second countdown starts, during which audio for the Ghost is recorded. B holds a mug up in front of him, and it is captured at the end of the countdown. The Ghost, comprising both the mug and recorded audio, is then transmitted to A's corresponding wormhole. (d) Later, A receives the Ghost from B at the Wormhole endpoint on her fridge.

plete connection, taking a photo of the marker on their chosen artifact, and assigning it a label. In our technology probe, participants in each pair were given an opportunity to either freely place their markers, or coordinate with each other during the onboarding video conference call to set up their wormhole connections. Connected wormholes will appear in each user's list of connections with an image and label (Figure 4.4). This process can be repeated for new wormhole connections. To edit the artifact of a wormhole endpoint, a user can simply move the printed marker to another artifact and update the label accordingly.

Figure 4.4: Screenshots from the setup app showing a pair of remote partners A and B use the setup app to establish a Social Wormhole connection. From left to right: (a) A initializes a Social Wormhole connection with her 'fridge' as an endpoint. (b) Remote partner B views the incomplete connection initialized by A and taps the photo icon to begin to complete the connection. (c) B taps to take a photo of his wormhole marker. (d) B names the marker 'shelf' to correspond with its physical location. (e) This completes the connection, now indicated by the solid green line.

4.2 Methods

In order to gain insight into how people would leverage and behave around a ubiquitous constellation of distributed and physically grounded artifacts for social connection, we designed and conducted a two-week field study with pairs of remote friends in their respective homes using the Social Wormholes technology probe. In this section, we elaborate on the study procedure, measures, and approaches used for data collection and analysis.

4.2.1 Participants

12 pairs of participants (24 people total, including 10 females and 14 males) completed the study in full (see Table 4.1) and were recruited from a technology company using an employee mailing list and internal communication channels. Participants were recruited in pairs who considered themselves friends, except for P5 and P6 that was formed ad-hoc and did not know each other before the study. We recruited from a diverse set of teams within the company, representing a wide variety of technical and non-technical background including HR, sales/marketing and

Table 4.1: Self-reported demographic information of our participants who completed the study.

Pair Number	Gender	Age	Education Level	Ethnicity	Relationship (IOS Scale [9])
P1a	Man	36	Bachelor's Degree	White	4 = equal overlap
P1b	Man	37	Bachelor's Degree	South Asian	3 = some overlap
P2a	Woman	30	Bachelor's Degree	Not Reported	2 = little overlap
P2b	Woman	27	Master's Degree	East Asian	2 = little overlap
P3a	Man	28	Master's Degree	East Asian	5 = strong overlap
P3b	Woman	27	Bachelor's Degree	East Asian	4 = equal overlap
P4a	Woman	23	Bachelor's Degree	Hispanic	4 = equal overlap
P4b	Woman	27	Bachelor's Degree	White	5 = strong overlap
P5a	Woman	21	High School	East Asian	1 = no overlap
P5b	Woman	21	Bachelor's Degree	East Asian	1 = no overlap
P6a	Woman	26	Bachelor's Degree	South Asian	1 = no overlap
P6b	Woman	30	Master's Degree	South Asian	1 = no overlap
P7a	Man	27	Bachelor's Degree	White	5 = strong overlap
P7b	Man	27	Master's Degree	White	5 = strong overlap
P8a	Man	31	Master's Degree	White	7 = most overlap
P8b	Man	31	Bachelor's Degree	White	4 = equal overlap
P9a	Man	32	Bachelor's Degree	White	3 = some overlap
P9b	Man	30	Some College	White	3 = some overlap
P10a	Man	32	Bachelor's Degree	White	4 = equal overlap
P10b	Man	32	Bachelor's Degree	White	3 = some overlap
P11a	Man	29	Master's Degree	Hispanic	4 = equal overlap
P11b	Woman	30	Bachelor's Degree	East Asian	7 = most overlap
P12a	Man	30	High School	Hispanic	6 = very strong overlap
P12b	Man	28	Some College	African American	6 = very strong overlap

art/creativity. Participants were located in 17 cities including Los Angeles, New York, London, San Francisco, Pittsburgh etc. Two pairs of participants (P9 and P11) were in different time zones from each other. Participants' ages ranged from 21 to 37 years (M = 29, SD = 4). Fifteen of them had a Bachelor's degree, six had a Master's degree, three completed some college, and two were high school graduate or equivalent. On a 5-point Likert scale (1 = Not at All, 5 = Extremely Frequently), participants on average reported not using AR/VR glasses at all ($Mdn = 1$). Each participant was compensated with a $100 Amazon gift card for completing the study.

4.2.2 Procedure

Before the study, each participant was given a set of five printed wormhole endpoints, and a pair of AR glasses and instructions for setting up the glasses. On the first day of participation, two researchers remotely on-boarded participants in pairs during one hour long sessions conducted over a video call. Researchers asked participants to fill out pre-survey questionnaires, helped participants setup systems required for the study, and thoroughly introduced them to the *Social Wormholes* system. Participants were asked to consistently use *Social Wormholes* for at least 15 minutes per day for roughly two weeks. They were also asked to answer daily survey questionnaires that consisted of four open-ended questions about their usage through an online form. Participants used Wormholes for 11 days on average, with a maximum of 14 days. On the last day of the study, two researchers held an hour-long exit interview session with participants. Participants were interviewed in pairs. Finally, participants were also asked to complete an online exit survey. All surveys were issued via Google Forms.

4.2.3 Measures

App Log Data

We recorded log data of participants usage of *Social Wormholes*. This includes information on markers — when they were installed and what names were given to them, and content — when were the ghosts and sparkles sent, which Wormhole endpoint they were sent from and sent to, and what content was transmitted. Data such as the Wormhole endpoint labels and the number of transmissions made per day were automatically logged by the phone-based setup app and the AR glasses connection app respectively. We utilized the log data in our qualitative and quantitative analysis.

Pre-Survey

During the onboarding sessions, each participant completed a pre-survey. This included questions on demographic information (i.e., age, gender, education level, ethnicity), previous AR/VR experience, level of loneliness using the short-form measure of loneliness (ULS-8) [67], and the closeness of the partners' relationship with each other using the single-item Inclusion of Other in the Self Scale (IOS Scale) [9]. The ULS-8 [67] contains 8 items (2 positively worded, which are reverse-coded), that should be rated on a 4-point scale (1 = Never 4 = Often). Examples of statements include "*I lack companionship*," and "*I am an outgoing person*." The IOS Scale [9] asks people to select a single option on a 7-point scale (1 = Not at all close, and 7 = Extremely close), "Which picture best describes your relationship with your study partner?" A set of pictures with progressively overlapping circles, labeled “Self” and “Other” were provided to give a visual indication of the options available. See the supplemental materials for more details.

Daily Survey

We asked participants to fill out a daily survey (refer to the supplemental materials for example questions) during their participation, which comprised multiple choice, Likert, and open-response questions. Custom Likert scale questions based on specific features of the Social Wormholes technology probe were issued, such as: “*Symmetric connections improved my sense of partner’s state over asymmetric connections*,” (1 = Strongly Disagree, 7 = Strongly Agree). They were also asked open-ended questions about what types of activities they engaged in over the day, whether they modified their Wormhole connections, what they tried to transmit, and how they perceived transmissions from their remote friend (e.g. “What activities do you think your study partner engaged in while using Social Wormholes today?”). Participants were reminded to complete the survey via daily calendar events that were scheduled in negotiation with them. They completed them with respect to their prior full day using the probe.

Exit Survey

At the conclusion of the field study, participants were asked to each answer an exit survey (see supplemental materials). This exit questionnaire included questions that revisit their level of loneliness and relationship with their study partner using ULS-8 [67] and IOS scales [9] to capture a post-intervention measure (see descriptions of these scales in Section 4.2.3 or refer to the supplemental materials for more detail), and a longer and more comprehensive set of closed-ended and open-ended questions on their setup and usage of the technology probe. Examples of questions include, “Where is Wormhole X, and how did you decide this?”, "X affected where I placed my Wormhole markers.” One question also inquired about the sense of presence: “While using Social Wormholes, I can feel my study partner's presence in my space (1 = Strongly agree, 7 = Strongly disagree)."

Exit Interview

To conclude the study, the researchers conducted semi-structured interviews with participant pairs over a video conferencing call. Interviews were based loosely on the pre-prepared questions (see the supplemental materials) that were used to elicit their thoughts and feelings with respect to using Social Wormholes. Unscripted follow-up questions were asked to dig deeper into points raised by participants. All interviews were recorded with participants' consent and were later transcribed. Each interview lasted approximately 60 minutes.

4.2.4 Data Analysis

A combination of quantitative and qualitative data was collected using the aforementioned measures. Total counts for connections, endpoints, and transmissions were extracted from the app log data, and were furthermore aggregated and analyzed per pair of participants (Table 4.2). Grand averages were computed from the IOS scale for relationship closeness, and from the ULS-8 scale for loneliness. Sense of presence was computed from the responses to survey questions (Table 4.3).

Table 4.2: Descriptive statistics for transmissions and connections, reported over the time duration of the entire study. Data in this table was collected from the setup and connection app usage logs. Total count includes everything created during the course of the field study across all participants.

Asset	Total Count	%	Mean/Person (SD)
Transmissions	2416		
Ghosts	576	23.8%	23.46 (14.01)
Sparkles	1840	76.2%	75.33 (45.94)
Connections	54		
Asymmetrical	39	72.2%	3.93 (1.22)
Symmetrical	15	27.8%	1.07 (1.22)

The exit interviews were transcribed and sectioned into quotes for a bottom-up, open-coding approach to data analysis. We iteratively coded the collected interview quotes, then merged their findings to identify the common themes. Two authors collaboratively performed open coding [138] on the interview quotes to arrive at an initial set of codes. Then, affinity diagrams [71] were built, and groupings emerged that highlighted an array of behaviors, perspectives, preferences, opportunities, and concerns. Several authors conducted weekly meetings to review and refine codes, themes, and design implications. We report on these themes in Section 4.4.

4.3 Social Wormholes Usage

24 participants (12 pairs) completed the study. One person traveled and had to re-establish the location of her wormholes during the course of the study. We logged 576 Ghosts and 1,840 Sparkles transmitted between participants, and collected 24 pre-survey responses, 118 daily survey responses, and 24 exit survey responses. We report on our findings of how people used the technology probe during the study, including what artifacts people assigned as connections, how they chose to map them together, and how they used the flexible number of connected artifacts.

4.3.1 General Usage and Self-reported Effects

Volume of Transmissions: Participants initially installed 129 wormholes with 47 types of artifacts (*e.g.* desk, kitchen, wall, bedroom), and in their exit survey responses they reported 125 wormholes with 25 types of artifacts. During the field study, 1,840 Sparkles and 576 Ghosts were transmitted. Participants on average sent 23.46 Ghosts (SD = 14.01) and 75.33 Sparkles (SD = 45.94) to their study partners throughout the study. Refer to Table 4.2 for a summary of these metrics.

Effects on Social Connection: Participants reported that the technology probe significantly decreased their feeling of loneliness and increased the feeling of connectedness with their study partners. The mean ULS-8 loneliness score was lower for the post-measure (M = 1.65, SD = 0.51) than the pre-survey measure (M = 1.77, SD = 0.49). A one-sided Wilcoxon signed-rank test on participants' responses to the short-form measure of loneliness (ULS-8) [67] before and after the technology probe (collected in pre-survey and exit survey respectively) shows a statistically significant decrease in participants' feeling of loneliness, with Wilcoxon statistic = 144.5, p = 0.022. Regarding relationship closeness, the median scores from the IOS Scale for the pre- and post-measures were equivalent (Mdn = 4). However Through an additional Wilcoxon test on participants' responses to the Inclusion of Other in the Self Scale (IOS Scale) [9] before and after using Wormholes, we also observed a statistically significant increase in their connectedness ratings,

Table 4.3: Statistics for survey questions. Pre- and Post- measures were captured in the pre-survey and exit-survey respectively. A median is reported for relationship closeness and sense of presence since they were based on a single-item measure, while the mean is reported for loneliness since the scale comprised multiple items.

	Pre		Post	
	Average	SD	Average	SD
Relationship Closeness (IOS [9])	Mdn = 4	1.86	Mdn = 4	1.74
Loneliness (ULS-8 [67])	M = 1.77	0.49	M = 1.65	0.51
Sense of Presence	N/A	N/A	Mdn = 3.96	1.67

with Wilcoxon statistic = 5.5, $p = 0.0024$. Statistical analysis shows that participants' responses indicated they were significantly less lonely and had stronger connections to their study partners after participating in our study and using Wormholes. Data on these metrics are included in Table 4.3.

Effects on Sense of Presence: Alongside feelings of connection and loneliness, participants also indicated an increase in their sense of presence of their remote study partners in their physical space when using the technology probe. We observed a statistically significant correlation ($r = 0.454$, $p = 0.020$) between the number of transmissions (captured in the log data) and participants' ratings to the exit survey 7-point Likert scale question "*While using Social Wormholes, I can feel my study partner's presence in my space.*" (1 = Strongly Agree, 7 = Strongly Disagree). This suggests that participants who received more transmissions during the study reported a stronger sense of their study partner being with them. In the daily survey, P10b commented *"I saw Sparkles from the desk area wormhole, which made me feel like they left their presence for me to discover."* Data on this metric is included in Table 4.3.

4.3.2 What Physical Artifacts Are Used?

During onboarding for the technology probe, participants were guided to choose a vast array of physical artifacts in their homes to configure as wormhole endpoints, spanning from small objects, furniture pieces to wall surfaces of a room. With this customizability, we want to understand what types of physical artifacts people choose to use to stay connected and how they use them for communication.

What artifacts did people use?

During set up based on log data, participants initially put their wormholes on 47 types of artifacts, with the top five most popular options being a desk (22), kitchen (11), fridge (6), wall (6), and door (6). In the exit survey, the participants were asked where the wormholes were by the end of the study and whether or not they had been moved. Wormholes converged to a smaller subset of 25 types of artifacts, the top six being a desk (29), kitchen (14), wall (9), bedroom (9), fridge (7), and door (7). Through the process of the study, participants have explored and thereafter discovered what artifacts they prefer to use as connections.

This suggests that many participants chose to configure wormholes on common household objects and spaces. During exit interviews, some participants shared that they connected artifacts that are very personal and special rather than commonly intended for communications. P3b, P4a&b and P10a centered their communication to their shared hobbies, such as playing piano [P3b, P10a] and sharing tarot cards.

> *"My favorite part was when I saw sparkles at his piano wormhole and heard him playing music — it made me so happy as he has been helping me look for a piano to begin lessons and I remember him telling me that when he plays piano he feels happy or relaxed, so I was also happy for him!"* – P3b

P4a and P5b experimented with putting the wormhole on their pets or capturing playful moments of their pets[2].

> *"I think it was pretty special when I sent you a ghost of my dog, which was also really hard to do because it kept moving around, and I just trying to track and follow them. "* –P4a

[2]Participants confirmed that no animal was harmed during the study.

“I just waited until he [P5b’s cat] was laying down, and then the first time when I made the connection it worked, he was staying still and everything. Next time he was not friendly [laughter].” – P5b

How did people choose the artifacts?

From the Likert-scale question in the exit survey, “_ affected where I placed my wormhole markers. (1 = Strongly Disagree to 7 = Strongly Agree),” participants reported routine ($Mdn = 6$), environmental lighting ($Mdn = 6$), wormhole marker size ($Mdn = 4$), and household occupants ($Mdn = 4$) to be the factors that mattered the most for determining the placement of the wormholes.

Many participants placed their wormholes in a manner that suited their daily routines. This suggests that people desire connection technology to be seamlessly integrated into their existing environments, around spaces in their homes in which they regularly frequent while following their normal routines. P5b, for instance, reported choosing artifacts specifically for connecting over everyday meals:

“It’s by my stove, since I also visit the kitchen frequently. I thought it would be nice to connect with my partner over the food we are eating.” – P5b

Artifacts that are located close to people’s routines tended to get used more often than others. P4b explained that he used the wormhole in his kitchen the most because lots of routines happen around it:

"It was just the one that I had the most to do around it. There were my coffee mugs there, there were my dishes, my food, my stove, so I thought about doing it more when I was at that one than any other one." –P4b

As another factor affecting where they placed wormholes, participants considered how well the wormholes fit into their space (echoing two of the factors found in exit survey: the wormhole marker size and other household occupants). P11 explained in the exit interview for not wanting the wormholes to clutter her space, while P3 elaborated that she wanted to customize the wormholes to fit her home decoration:

> *"I just wish that instead of these markers, I had a cute little object that was unobtrusive and looked like a decoration that would trigger these things instead of a wormhole, because it doesn't go with the rest of my vibe in my house."* – P3b

Additionally, one pair of participants [P7a & b] commented that they would choose artifacts based on special occasions. When they saw interesting things outside their residence, they wished there was a wormhole to share it. P7a brought the wormhole to places outside their routine so that they can capture interesting things there, such as pool and baseball games. One participant, P2a, selected an unusual and awkward artifact for the sole purpose of making a joke:

> *I also put it in funny places because I think it should be a light-hearted thing...I put it up with toilet where you sit on the toilet and it's on the wall right next to you. It's really funny.* - P2a

4.3.3 How are Artifacts Connected to One Another?

Social connection systems are often designed to be symmetrical, meaning that identical artifacts are used as a point of connection (e.g. A's candle is connected to B's candle). In this technology probe, participants chose to map things symmetrically and *asymmetrically* (i.e. when the artifacts are different, such as a patio table to car). We report on how participants configured their connections to elucidate how people draw interpretations from social connections.

Symmetric vs. Asymmetric Connections

Participants established 54 wormholes connections (15 symmetrical, 39 asymmetrical) in total with our technology probe over the duration of the field study. These metrics are summarized in Table 4.2. Participants indicated in the exit survey that symmetric connections improved the sense of presence with their partners, and made it easier to understand their partner's state and share their own state. Asymmetric connections led to special experiences.

In our daily surveys, participants agreed (rating of 4 or higher) with the statement *"Symmetric connections improved my sense of partner's state over asymmetric connections,"* 75.3% of the time (Mdn = 4); and agreed (rating of 4 or higher) with the statement *"Symmetric connections make it easier to share my state over asymmetric connections,"* 80.4% of the time (Mdn = 5). For example, P9a&b mentioned connecting their refrigerators to share cooking moments with each other, while P12a&b described how symmetrical connections at their desks made their communication experience more immersive and helped them get a sense of working together.

Participants made many different types of asymmetrical connections including connections between one participant's TV [P2a] their partner's fridge [P2b], between one participant's plant [P2a] to their partner's toilet [P2b]. In addition, P2b kept all of their wormholes on their desk, while P2a scattered their wormholes throughout their house—their desk, TV, the wall next to their desk, their shower wall, and their car. While asymmetric connections might not be easier for participants to understand and share with each other, participants reported that the asymmetry produced a special, interesting experience:

> *"I do really enjoy asymmetrical experiences because my partner would have her wormhole on her cat for example, which will spice up the experience as a whole and keep it interesting."* – P5b

How Connected Artifacts are Interpreted by Users

We synthesize from daily surveys, exit surveys, and exit interviews that participants saw different degrees of value in the location of their artifacts. Some appeared to have a more spatial understanding of their connections; others focused on connecting over shared activities.

Participants with strong spatial interpretation likened the experience to having a sense of presence [P10b] or leaving notes for each other around the house [P6a]. In daily surveys, participants reported that knowing where the transmissions are coming from adds significant value in understanding their partners' activities and daily routines.

> *"I would say it was very unique. It reminds me of my parents would leave notes around the house when they were not there. You're not expecting it and then you stumble on it."* – P6a

Others, rather than placing significance on where their artifacts were located, simply saw the connections as a direct channel of information exchange to their partner. Participants rated the statement "*I felt that it was valuable to receive transmissions at particular places.*" in the exit survey with an overall neutral score (Mdn = 4). For example, P11 stated that she prefers a direct form of communication and would like the wormhole to be "*partner-based*" instead of "*object-based*":

> *"It will be great if they can be customized, and I decide that in my room, this is [P11b]'s wormhole, and then I can glance at it any day I want, just to see her messages to me. "* – P11a

Still others interpreted the wormholes connections as their partner's state of activity. 29 daily survey responses reported using wormholes to share activities. Our participants experimented with using Wormholes when working (reported 15 times in daily surveys), eating (14), doing chores (13), cooking (11), walking around (10), getting ready in the morning (8), watching TV (6), playing music (5), organizing/trying on clothes (5), driving (2), and doing laundry (1). In exit interviews, P10b stated that he frequently used wormholes to signify his work status. He tried to communicate a break in his work day - making coffee, singing to music, looking in the fridge. P2a reported working at his desk and transmitting a Ghost of his keyboard and mouse. P12a enjoyed connecting with their partner while working and experienced a strong sense of working together: *"I can imagine himself typing when I'm typing"* -P12a .

Through a sequence of asynchronous transmitted artifacts, some users were able to interpret a sequence of transmissions as a continuous line of daily activities from their partner:

> *"I saw Sparkles coming from their door and their coffee machine, so I figured she must be starting her day; I saw lots of Sparkles by the kitchen and door, which made me think she was cooking before she left. "* – P4a

P7b and P5a stated they used the wormholes to track routine activities throughout the day, wherever they went:

> *I'm at my desk, I'm drinking water. I said, I'm ghosting my water bottle or I just finished washing my face [...] I sent a my skincare or even my fan when it's hot outside of summer. [...] Oh yes, and then also washing the dishes.* – P5a

4.3.4 How Many Artifacts Are Used?

Social Wormholes system log data and daily surveys show that 23 out of 24 participants who completed the study used more than 4 wormholes everyday. Most participants preferred to have large quantity of distributed connection endpoints. In exit interviews, participants reflected that the distributedness provides better coverage and a more diverse communication experience with their friends:

> *"[With] a greater number, I could definitely explore more options and get a more, a larger variety of contents. Just to learn more about like where she is at a moment versus having fewer. If we did have fewer wormholes, it might just be the same few things that are happening."* – P5b

P5 and P6 also mentioned the distributed wormholes made the experience of maintaining awareness with their study partner feel like a "scavenger hunt" in a good way:

> *"It was a treasure hunt of like, 'Oh, where will I see it?' That experience was really cool."* – P6a

Large number of wormholes also support spur-of-the-moment sharing and encourage participants to use wormholes for a variety of reasons. 31 comments from the daily surveys indicated that participants were motivated to use wormholes when they were physically around the wormhole location.

On contrary, other participants mentioned in exit interviews that having a large number of wormholes might make it inconvenient for them to check messages. Some preferred using only one wormhole or a centralized location for all wormholes. According to the log data, P12a mainly used one wormhole endpoint throughout the user study (i.e. used one of their endpoints more than 80 times, and used others less than 5 times). In the exit survey and interview, P11b shared how she compiled all wormholes together for ease of use:

> *" I think in the beginning, we had [the wormholes] placed in different corners and I eventually just consolidated them. I had them in the pile near my desk. I always go through them in order."* – P11b

4.4 Themes and Design Implications

Following exit interviews open coding and affinity diagram analysis (see Section 4.2.3), we report on the set of themes of people's behaviors and resulting preferences when given the power to create their own ecosystems of connected objects for social connection, which include people's broader patterns of behavior for using ubiquitous, physically-grounded social connections throughout their day (Section 4.4.1) and what each of their connection endpoints represents to them (Section 4.4.2). We summarize our results and present our design implications for future physically distributed social systems in Table 4.4. We also reveal how people adopt a mosaic of behaviors around how they use these social connections (Section 4.4.3), and other important social considerations for these social connections such as privacy (Section 4.4.4).

4.4.1 Behavior Patterns Around Communication

Based on users' self-reports, descriptions, and comments of their usage from exit interviews, we discover two clusters of behavioral patterns toward exploring the technology probe as a communication medium: ritualistic and serendipitous. A ritualistic behavioral pattern leads users to seek efficient and stable means of sending and receiving messages. A serendipitous behavioral pattern motivates users to be experimental and creative about their process of connecting with others.

Ritualistic Communication

Some participants [P4a, P5a&b, P9a&b, P10b, P12a&b] establish a predictable and ritualistic pattern in their daily communication. They placed their wormholes on artifacts they were using everyday and integrated the physically-grounded communication in conjunction with routine moments of their life, such as placing one on their bedroom mirror to share their outfits in the morning or on their coffee machine to share information about their breaks.

Both P4 and P9 reported sharing outfits of the day with their study partners habitually. P4a described when she was getting ready, she sent her outfit to her partner through the wormhole on the mirror, to show what she was wearing that day. P4b described her enjoyment receiving her study partner's daily update of her outfit: *"I really enjoyed the Ghosts that she sent with her mirror because I could tell that she was having fun there. "* – P4b

Participants P5a and P7b described in detail how they shared a constant sequence of their routines throughout the day. Participant pairs P5 and P9 developed a closer relationship with their partners by learning about their routine activities and environments:

> *"He has a bit of like routine that I didn't know. I thought he just works and then goes and falls asleep until he comes back to work. I found out that he has a lot of the cooking routines and some of the stuff he would send me, just you can see a pattern."* - P9b

In ritualistic communication, users' mappings were usually symmetrical, which made it intuitive for them to interpret the activity or space of their partners. To maintain a predictable pattern, they often desired to receive all the messages at expected places. This meant that they often only use a small set of fixed connections so that they would not miss out on any messages [P9b, P12b].

> *"For me, I would have preferred three or less. I think it would have just been more convenient and easier to keep up."* - P12b

Future systems can support a predictable and ritualistic communication experience by being designed to keep a long-term record to the connected artifacts along the user's routine. The system may also learn about the user's routine and recognize any small change of habits over time, in order to help users realign the connection points to their daily lives. Since symmetrical mapping is most intuitive for connecting partners, the system should prompt the users to establish symmetry during set up and maintenance. To avoid missing messages, users would appreciate a notification or a centralized channel to recover messages for a sense of control and reassurance.

Serendipitous Communication

Several participants [P2a, P3a, P4a&b, P7a&b, P10a, P11a] exhibited a serendipitous tendency towards how they used Social Wormholes. Participants also displayed serendipity by entertaining their partners with hobbies [P3b, P4a&b], playing with pets[P4b, P5a], making jokes[P2a], or sharing interesting occasions and events[P7a&b]. People behaving serendipitously found it important to incorporate some novel artifacts or something else that is different from the day before. They struggle to see the value of transmitting a routine object.

> *"I found a hard time to everyday find one single object that I would want to send to [11b]... maybe if I got a new pair of shoes and I want to send the one shoe to her."* - P11a

Users with serendipitous tendencies experimented with unconventional artifacts (i.e. non-standard household objects) as connection points. Examples include moving objects, pets, locations that provoke humor, and artifacts related to personal hobbies. The mapping of connections were often asymmetrical and changing, as the users preferred to spice things up, keep things fresh, and react to momentary changes of events. For both sending and receiving, users embraced a large number of connections so that they could share wherever and whatever they wanted and so that they could have the treasure hunt-like experience of finding messages by surprise [P6a].

Future systems can support and encourage serendipitous communication by adopting high customizability and flexibility in terms of what artifacts can be activated as connection points. The system should instigate the discovery of potential creative wormholes and transient changes in mapping connections. Changes in connected artifacts and mapping should be tracked and streamlined by the system rather than burdening users to provide accurate labels. Since a greater number of connection points leads to more spontaneous and surprising sending and receiving, future systems could multiply the amount of surprising opportunities by expanding to include one-to-many, many-to-one and many-to-many connections.

4.4.2 What Physical Artifacts Represent

Learning from how artifacts are connected and interpreted by users, as well as users' comments and reflections, we notice that people configure physically-grounded connections with different ideas for what they represent. Artifacts could be interpreted in three ways: as a proxy for a person, as a means to connect a user's space with their partner's space, or as a means to share an activity with their partner.

Artifacts as Proxies for People

From their comments in exit interviews, we notice that several users [P2b, P4b, P7a & 7b, P11a] considered their connected artifacts to be direct channels to—or proxies for—their partner.

This behavioral pattern parallels the concept of reaching someone with a smartphone or land-line phone. In this paradigm, the location of a partner's phone is not necessarily important; rather, the fact that a person can be reached through it as a medium takes precedence. Similarly, artifacts could serve as a proxy for a person by substituting for another person's presence in a space. P4b and their partner P4a both lived alone, but they interpreted the wormholes as representations of their partner in their respective spaces, like *"having a low-impact roommate"* - P4b. While some participants stated one proxy was enough [P7a, P9b], others accepted the idea of having many proxies spread out across multiple locations in their homes. In this way, they could even provide a tour of their house [P10a]. In yet another case, some people began to consider that even the content that was transmitted (and not just the wormhole itself) were proxies for their partners. For example, P7a and P7b came to associate the transmitted ghosts of their favorite beverages as stand-ins for each other.

We noticed that this general viewpoint for wormholes served two purposes: to act as "shrines" and to act as wearable connections.

Regarding "shrines", people treating wormholes as proxies for other people found it important to mark a personal artifact of significance as a connection endpoint (e.g. a special figurine that signifies their friend) [P3b]. This mirrors former designs in Ambient Media that have a sentimental or personal nature [25, 69]. For receivers, the location to where the physically grounded receiving endpoints are placed in their own environment is rather significant. The placement speaks to the relationship with the person. For an intimate loved one, the receiver might place its artifact proxy in close proximity and private location, such as a nightstand. For a colleague, the receiver might place its proxy at a location that mirrors their relationship, such as a desk.

Future systems could support this perspective by being aware of the relationships between the user and their friends. Current social media has developed relationships classifiers in the social network; for example, Facebook includes groups of friends based on closeness and how they met. This kind of relationship network can be extended to physically-grounded connections by mapping people's relationships to physical artifacts and spaces. With this knowledge, future systems could assist users maintain their connected physical environment meaningfully and orderly based on their personal relationship network.

Regarding wormholes acting as wearable connections, some people treating wormholes as proxies for others expressed a desire for a wearable wormhole [P7b] or one they can carry around in their wallets so they could easily send and receive content from their partner instantly. As the connected artifact is kept on the user's person, its relative position with respect to environment is not significant. However, they might still be interested to keep track of how their partner's location changes throughout the day.

Future systems could design around the ability to get instant updates about their partner's location. For instance, if the receiver is using one wearable wormhole and the sender is using multiple location-based wormholes, then the sender's many endpoints can be used as a light-weight form of location tracker. The receiver can be notified on their wearable wormhole whenever the partner moves to a different location. Compared to a GPS location tracker, this format gives the sender a great degree of control over what locations are being tracked and shared with others.

Artifacts to Create Overlapping or Connected Spaces

Some participants [P4a, P5a, P6b, P9a&b, P10b, P12a] considered their connected artifacts to be a means of connecting their spaces with their partner's spaces, similar to the literal concept of a wormhole. By establishing wormholes with this viewpoint, they gained a sense of presence of their partner [P5a, P9a&b, P10b] and appreciated that having connected artifacts could make it as though their friend can co-inhabit the space with them [P5a, P10b]. Some people also associate connected artifacts with the concept of leaving notes for each other around the house [P9a, P6a].

For these users, being able to choose multiple artifacts that can be seamlessly integrated into different parts of their homes is helpful. The specific artifact that is chosen is less important than how the artifacts are positioned within the connected spaces. P4a and P9a commented on the desire to have a greater degree of spatial co-relationship, such that they can position transmitted objects in their partner's space mirroring positions in their own space.

> *[M]ake it a little bit more immersive and to feel like I'm in her space, I think it would have been cooler if it was more of a 3D image and if it was a specific place, especially if it could be wherever it was in relation to her wormhole. If she has her coffeemaker that's off to the right of her wormhole, so she takes that photo, I'd want to have to look at the same place to see where is her coffeemaker in relation to my wormhole.* - P4a

Symmetrical mapping of spaces is the most intuitive and works best to support a sense of presence. Future systems could incorporate computer vision technology that plays a role in recognizing the similarity between the physical spaces of both parties and makes suggestions to how spaces should be connected. Future systems could also use computer vision data to accurately map the spatial co-relationship between transmitted object and the connected artifact, enabling a 3D hologram representation of the transmitted object placed in the connected environment with meaningful spatial mirroring.

Additionally, the number and placement of connected artifacts may have an effect on the sense of presence. Future systems may optimize by suggesting centrally located artifacts in a space as connection points, such that more surrounding objects can relate to them spatially. The number of connected artifacts could be scaled based on the system's understanding of the size of the user's environment and the spatial coverage of each connection point. An optimized number of connections would help achieve a symmetrical spatial coverage between connected spaces and therefore maximize sense of presence.

Artifacts for Sharing an Activity

Several participants [P4a, P5a&b, P7a&b, P9b, P10a&b, P12a] considered their connected artifacts to be places in which to participate in a shared activity with their partner, aligning with many prior works on sharing activities over distance [14, 24, 113], in which cooking and dining are popular themes. By employing symmetrical connections, these participants vividly perceived themselves sharing activities such as cooking [P5b] or working [P12a] together. Participants also dedicated wormholes for the sole purpose of sharing special hobbies (piano [P4a, P10a]) and events (pool party and baseball game [P7a&b]).

Many participants enjoyed connecting asynchronously through activities. They interpreted a stream of transmissions from their partner's different wormholes as continuous daily activities [P4a], which gave them a strong sense of co-presence with their partner. Building on this, P9b desired to have sequencing and grouping features to better illustrate how their partner transitioned between activities.

> *"I would like to see it as a story of five different ghosts, in order of which they were transmitted back to back. From my perception, that would give me a sense of seeing their life together [...] If you tell the system what you are doing, then it can group those objects by story. If I'm cooking then I want send those multiple things from my kitchen, groups them together. "*- P9b

Interestingly, our technology probe was designed to support asynchronous connections, and yet, some users gravitated to having synchronous experiences, underlining the significance of supporting synchronous activities while maintaining the poetic sense of asynchronous ambient connections.

> *"...suddenly I knew we were both live in the moment together, that would have been maybe meaningful where we could connect, but there was really no way to align. Are we two ships sailing passing in the night or are we having a moment because we're here in the moment together?"* - P10a

Future systems for supporting the notion of shared, connected activities should identify which common activities both connected partners engage in and suggest a symmetrical mapping of connection points in the vicinity of that activity to the users. Future systems could identify activity-signifying artifacts (e.g.piano) as its suggestions. There is also an opportunity to recognize the context of the activity in order to determine whether users would desire a synchronous or asynchronous sharing experience. Last, some activities may benefit from one-to-many broadcasting or many-to-many connections. A multi-location alumni reunion is a good example of such an activity. Future systems could explore how to support such synchronous and scalable connections, and how to mitigate multiple sequences of activities in a network of physically-grounded connections.

4.4.3 Mosaic of Behavior Patterns and What Connected Artifacts Represent

Emerging naturally from using the customizable technology probe, our findings reveal that people adopt multiple behavioral patterns and find values in all of them simultaneously.

Some participants predominantly displayed a ritualistic behavior pattern, but also enjoyed rare moments of serendipitous playfulness. P5b, as an example, found value in learning routine details about their partners' daily life, but also took a spur-of-the-moment experiment using their cat as a connected wormhole. In some cases, the two partners in participant pairs adopted opposing communication patterns while connected in the same ubiquitous ecosystem. For example, P10a is serendipitous, while their partner P10b is ritualistic.

Participants also adopted different viewpoints for what each of their connected artifacts represents. For example, P7a established some connected artifacts acting as proxies of their partner and other connected artifacts acting as places from which to share an activity. Their favorite beverage served as a proxy of the partner on a daily basis, but during an interesting event such as a pool party, they dedicated a wormhole to being a way to transmit activities taking place during the event.

Given this behavior, we think that there is not one superior behavior pattern that physically grounded social connection technologies should cater to. Rather, we anticipate that many of these different perspectives can co-exist in people's lives and in ubiquitous computing as a mosaic of different types of connected artifacts.

4.4.4 Other Social Considerations

While we focused on patterns of behavior that people exhibited, users also brought up considerations that are important to the design of future ubiquitous computing systems for social computing.

Privacy

Generally, people were comfortable sharing with one another since they were friends, but comments regarding privacy did arise [P6a, P9b, P10 a&b]. Some users hesitated or had questions about what the glasses captured and what we as researchers would be able to see. Future systems will likely need to clarify how privacy is maintained and protected by companies providing such services. We also anticipate that as the number of connected artifacts scales upwards, people may lose oversight of what objects are connected and sharing information. Furthermore, while our technology probe used printed markers, it's possible that future systems can invisibly tag artifacts. This can exacerbate this potential issue. One possible solution for future investigation is establishing tools or methods for automatically curating and reviewing the information that is being shared through a person's network of connected artifacts. Tools that can give users an overview of all of their connections may be particularly useful.

Overwhelming v.s. Loneliness

Despite there being more platforms than ever for online social connection, there is nevertheless a growing epidemic of loneliness. Furthermore, there is a problem around applications and their constant demand for our attention. These negative effects could extend into the realm of physically-grounded and connected artifacts, as one participant had speculated:

> *I feel like too many may feel a little overwhelming and intrusive. Then it turns into more of an inconvenient scavenger hunt, because yes, you constantly have to go around and look at a zillion different little things that you scan is or like, it could give you a bad reaction of loneliness, if you don't receive anything and you have a zillion different wormholes and you don't get anything. I feel like keeping it semi-small is maybe better.*
> - P9b

To address this issue, future systems might play a more active role in curating the number of available connections. They may be able to make suggestions to users and/or automatically increase or prune unused points of connection to optimize in accordance with users' needs and usage levels.

4.5 Discussion

Our investigative approach was unique from prior works in two ways. First, the vast majority of prior studies on the use of tangible or ambient systems for social connection have comprised a single pair or set of near-identical connected devices between remote parties [134, 38, 25, 87]. In contrast, by creating and deploying Social Wormholes, we gained knowledge into how ubiquitous computing—namely, an ecosystem of multiple artifacts— can be used. As expected, we found that ecosystems of multiple endpoints improve social connection and a sense of presence (see Section 4.3.1), similar to the range of single-connection systems. However, by studying the use of multiple lines of connection in concert with one another, we were in addition able to outline and distinguish between different patterns for social connection, as well as gain novel insight into how these patterns can co-exist with one another. Second, prior social connection systems have been designed based on researchers' own design intuitions or through co-design processes with users [38]. In other words, prior system configurations have largely been determined by researchers. Social Wormholes, instead, empowered pairs of friends to design and curate their own set of existing objects as endpoints for social connection on their own. This allowed us to learn what other objects and configurations may be fruitful, beyond those that have been previously identified, based on the usage patterns that emerged organically over the course of our two-week field study.

Stemming from our results, we discuss and contribute five points of knowledge to the prior literature regarding ubiquitous social connection systems.

First, we discuss that users value choosing their own artifacts. Designers may not always choose the artifacts that users themselves would and users would value this autonomy. With Social Wormholes enabling this ability, we found that several of the objects and places participants chose overlapped with those from prior literature (e.g. kitchen [24], bedroom [134], and mirrors [131, 38]) (see Section 4.3.2), thereby reinforcing that these are desirable to be used as endpoints for social connection. Furthermore, while our participants did not choose objects such as picture frames [25, 87], some of their comments underlined the appeal of using personal tokens that are specially representative of their remote friend (see Section 4.4.2). On the other hand, there were artifacts that our participants chose to connect that have not been used before in prior systems, such as toilets for humor and pets. These choices corresponded more with the desire to share fresh content (see Section 4.4.1). Ultimately, more study data is needed to capture the full extent of artifacts that would or would not be ideal for social connection. Nevertheless, future ubiquitous systems should therefore give users more autonomy to choose and update their own artifacts, not only to account for user's unique preferences and circumstances but also to support changing trends for artifacts, since users' ideas of what artifacts are interesting or fresh can change over time.

Second, we discuss that the surrounding context of routines and other people in the space shapes users' choice of artifacts. Routine was an important factor for users when choosing their artifacts (see Section 4.3.2). This strongly aligns with Cao et al.'s [23] highlighting of routine as a theme in remote communication. However, while some users allowed transmissions to occur as an accompaniment to their daily activities (see Section 4.4.1), others made it a deliberate and standalone practice to send transmissions (see Section 4.4.1). We also discovered that users are sensitive to how their choice of artifacts may affect or be perceived by other members of their household. To the best of our knowledge, our findings in this area are novel since most previous studies have focused on single users [59, 64, 69, 87, 134] or family units [82, 83] rather than studying the system in the context of a mixture of both users and non-users in the same household. Future designers should therefore anticipate that routines and other people, both users and non-users, are contextual elements that will shape users' choices and behaviors.

Third, we discuss the value of spatial context based on users' perspectives. Spatial information is most valuable to people who seek to connect through overlapping spaces (see Section 4.4.2) or through shared activities (see Section 4.4.2). Participants expressed a desire for transmissions to be presented in true spatial relationship to endpoints, expanding the perceived footprint of shared space and making transmissions more real and immersive. This echoes prior works that stress the importance of spatial coherency [88] and the preservation of physical-space information in virtually-mediated exchanges [46]. When connecting over a shared activity, the spatial information is valuable for adding a greater feeling of commonality and relation during an activity. For instance, participants enjoyed the illusion of their friend typing at their desk just as they were typing at their own desk. The spatial information adds an extra layer of social awareness [132, 66]. In contrast, when users center their perspective on the artifacts as proxies for people(see Section 4.4.2), they value the space as a context to the closeness of their relationship, and additionally, they value timing context of the messages. Thus, future designs should cater to capturing and relaying spatial information to enhance the user experience based on their perspectives.

Fourth, our findings add to prior literature on the preference around asymmetric spatial connections [149], in addition to symmetric connections. In contrast to the common assumption that people would prefer symmetrical pairings, a surprising 72.2% of connections with Social Wormholes were asymmetrical (see Section 4.3.3). Prior works on tangible systems for social connection have often been designed in symmetric pairs [98], placing heavy assumptions that symmetric connections are preferred. Our investigation directly studies how users choose to connect artifacts to one another and reveals the comparison between symmetric and asymmetric connections. We find asymmetric connections offer three advantages. First, asymmetric connections do not require effort to coordinate artifact pairs between casual friends. Depending on the closeness of their relationships, close friends and romantic partners may associate their relationships with a spatial context (see Section 4.4.2) and therefore choose to coordinate symmetric connections. Second, asymmetric connections can afford a serendipitous and fun experience, when users receive surprising messages at unexpected locations (see Section 4.4.1). Third, asymmetric connections can broadly support the mosaic of perspectives, as we find that the two partners in a connection pair often adopted opposing communication patterns (see Section 4.4.3).

Lastly, we discuss that distributed endpoints encourage opportunistic sharing and ambient receiving. From the sending perspective, distributed endpoints provide greater coverage around users' space and daily routine, making it easier to immediately share moments about their lives.

As such, Social Wormholes worked well to encourage sharing of more routine or "mundane" activities [146] during "empty moments" [102] in their everyday lives. From the receiving perspective, the distribution of endpoints enabled people to receive messages when their time and place were relevant, which catered well to people who enjoy ambient receiving. These users focus on going about their daily life and perceive social communication as an accompaniment in the background space [105]. Depending on the users' individual perspectives, the wide spatial distribution however also compromises the desire for instancy. Having to receive the message at the designated location introduced a potential time delay and required users to physically arrive at the corresponding endpoint to receive transmissions. In turn, it made some users feel that it was more difficult to "keep up" with all of the information (see Section 4.4.1), potentially leading to feelings of overwhelm (see Section 4.4.4). Future designers should consider when it might be helpful to limit the number of connections and/or incorporate notification features into a ubiquitous social connection system to strike a balance between ease of use for sharing and feelings of control in receiving information.

Table 4.4: Summary of our study findings in terms of themes, insights, and design implications from Section 4.4.1 and Section 4.4.2 for future physically distributed social connection systems.

Theme	Insight	Design Implications
Ritualistic Communication	Users integrate physically-grounded communication in conjunction with daily routines and seek efficient and stable means of sending and receiving messages.	Keep records of the artifacts along the user's routine, recognize changes in the user's routine over time and realign connected artifacts to their daily lives. Provide a centralized channel to recover messages for a sense of control and reassurance.
Serendipitous Communication	Users favor connections that are asymmetrical and changing because they add a sense of surprise to communication.	Future systems can prompt users with creative ideas for connection points and mappings. Expand connections to include one-to-many, many-to-one, and many-to-many connections.
Artifacts as Proxies for People	Some connected artifacts are interpreted as proxies for a person's presence in ones space, similar to "shrines."	Future systems can keep records of the relationships between the user and their friends, offering suggestions for artifacts and spaces that suit the nature of the relationship.
	Some connected artifacts are interpreted as direct channels to their partners, similar to a 1:1 chat. Users value instant updates from these, and they wish to carry the endpoints around as wearable devices.	Sparkles and Ghosts can allow users to share their location in a less intrusive way than GPS or other means. Partners wishing to share their location in a low fidelity way may embrace the usage of Ghosts to give context.
Artifacts as Overlapping or Connected Spaces	Some connected artifacts are interpreted as means of co-habiting spaces with partners for a sense of presence. Users prefer intuitive symmetrical mapping for this purpose.	Recognize similarity between physical spaces and suggest symmetrical connections. Map the spatial co-relationship between the transmitted object and the wormhole and enable a representation of the transmitted object placed in the environment with spatial mirroring.
Artifacts as Shared Activities	Some connected artifacts are used as channels for sharing particular activities. Users interpret interactions with the wormhole as signals that the partner is doing the activity.	Future systems can identify common activities that both connected partners engage in and suggest activity-signifying artifacts and spaces as connection points.

Conclusion

In this thesis, I explore a qualitative research approach that considers the understanding of space as an integral part of understanding people and uncovers design opportunities for technologies situated in space. I demonstrate with two research projects: designing blind navigation assistive technology in unfamiliar physical environments and designing social communication technology that promotes staying connected with remote friends in a physically-grounded, environment-centered way.

With respect to designing assistive technology, we find through an empirical study with 12 visually impaired participants(VIPs) that they desire to actively engage with the physical environments they are situated in and play an active role in exploring and learning the spaces. We established a holistic understanding of how navigation assistive systems(NASs) can be designed to support exploration. The users need two types of spatial information: *shape* and *layout* information to get a high-level overview of spaces and to make navigation decisions *in situ*. Their preferences for the format, source, and amount of spatial information vary between individuals depending upon their onset of vision impairment, their inherent sociability, and their O&M proficiency and mobility aid preference, respectively. The understanding leads to important design opportunities for NASs supporting exploration, including how NASs might facilitate spatial information in a manner promoting active engagement and how NASs can serve as educational tools to help VIPs build confidence in their O&M skills, thereby supporting VIPs' exploration in navigation.

With respect to designing social technology, we implemented *Social Wormholes*, an AR-based technology probe that enabled pairs of friends to craft an ecosystem of connected physical artifacts through which to transmit information. The probe allowed users to repurpose the surrounding spaces and artifacts as connection points, choose how they were mapped to one another, and how many connections they wanted at any given time. Through a field study with 24 participants, we uncover different perspectives and patterns of behavior for engaging with such a system. This includes ritualistic versus serendipitous behavior patterns and differing perspectives around whether these physical artifacts serve as a proxy for friends, as overlapping spaces, or as opportunities to connect over activities. Furthermore, we find that while different patterns of behaviors exist, users often adopt a personalized mosaic of these patterns. Our findings point to a future of ubiquitous, physically grounded social technologies that are to be designed and individualized to each person's values.

Through understanding space, this thesis reveals that design opportunities for future technologies are highly diversified and individualized, based on how users and technologies situated in space interact with one another, how users perceive the physical space, and what behavioral patterns users display around the space using technology. The diversity of perspectives dynamically contributes to user preferences interacting with technologies in spaces. It sheds light on many creative design opportunities for future technologies when researchers consider space as an actor in designing human-computer experiences.

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