Exploring the Design Space of Privacy-Driven Adaptation Techniques for Future Augmented Reality Interfaces

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Abstract

Modern augmented reality (AR) devices with advanced display and sensing capabilities pose significant privacy risks to users and bystanders. While previous context-aware adaptations focused on usability and ergonomics, we explore the design space of *privacy-driven adaptations* that allow users to meet their dynamic needs. These techniques offer granular control over AR sensing capabilities across various AR input, output, and interaction modalities, aiming to minimize degradations to the user experience. Through an elicitation study with 10 AR researchers, we derive 62 privacy-focused adaptation techniques that preserve key AR functionalities and classify them into system-driven, user-driven, and mixed-initiative approaches to create an adaptation catalog. We also contribute a visualization tool that helps AR developers navigate the design space, validating its effectiveness in design workshops with six AR developers. Our findings indicate that the tool allowed developers to discover new techniques, evaluate tradeoffs, and make informed decisions that balance usability and privacy concerns in AR design.

CCS Concepts

• **Human-centered computing → Scenario-based design**; **Mixed / augmented reality**; • **Security and privacy** → *Usability in security and privacy*.

Keywords

elicitation studies, threat modeling

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1 Introduction

As advancements in augmented reality (AR) hardware and sensing technologies make it increasingly feasible to use AR on an everyday basis, new privacy concerns arise for both end-users and bystanders. Biometric sensing used in natural AR interaction techniques—such as speech, gestures, and gaze—can reveal sensitive information about users, including their identities, health conditions, and personal preferences [26, 42, 50]. Environmental sensing and 3D reconstruction techniques can capture sensitive physical objects or bystanders without their awareness or consent [19, 57]. To enable users to maintain their desired level of privacy, which can vary across contexts and tasks, the security & privacy community is standardizing approaches for context-aware permission models to regulate the usage of AR sensing capabilities [2, 38, 63].

At the user interface development level, this raises a need to adapt AR interfaces to align with users' privacy preferences, maintaining continuity in the AR experience and minimizing loss of functionality, even when sensing restrictions are imposed. Existing context-aware adaptation approaches allow users to manually customize or automatically optimize AR visual layouts to serve usability and ergonomic needs [7, 14, 45]. However, developing AR adaptation techniques with privacy as the objective is challenging, as it often is at odds with usability. As such, it requires exploring a broader range of input, output, and interaction modalities to identify alternative design solutions. Our work takes two critical steps to address this problem.

First, we systematically explored the design space of privacy-driven AR adaptation techniques through an elicitation study with 10 AR researchers. Through analyzing AR interactions for two usage scenarios, the researchers produced proposals to accomplish core AR functionalities in more privacy-friendly ways. These proposals were designed to span varying levels of sensing access along a permission model and different system-driven, user-driven, and mixed-initiative adaptation approaches. Our analysis yielded an adaptation catalog of 62 techniques and overarching design strategies employed by the researchers to balance usability and privacy needs.

Second, we distilled our adaptation catalog into a visualization tool to make the design space approachable for AR developers without privacy expertise. Inspired by prior visual taxonomies of HCI systems research (e.g., Haptipedia [66] and Locomotion Vault [47]) and the AR researchers' design strategies, the tool maps adaptation techniques along sensing modalities and provides faceted search tools to compare alternative techniques. To evaluate whether our approach enables developers to design privacy-focused interactions without formal privacy training, we used the visualization tool to facilitate design workshops with six AR developers, where they selected adaptation techniques to satisfy different user personas' goals [21]. The developers reported that the tool enabled them to quickly navigate the design space, be more mindful of privacy considerations, and facilitate meaningful discussions around tradeoffs with usability and implementation effort. We conclude by discussing the future research needed to bridge the gap between our design space and the practical implementation of privacy-driven adaptation techniques in code.

2 Background and Related Work

Novel AR form factors and sensing capabilities can raise a variety of privacy concerns for both AR users and non-users [18, 61, 62]. In this section, we outline existing research on privacy risks and permission models for AR interfaces, as well as adaptive AR approaches. Then, we discuss key challenges developers face when attempting to develop AR systems that respect users' dynamic privacy needs.

2.1 Privacy Considerations for AR

We identify two main threads in usable privacy relevant to our work: *(1)* privacy risks arising from the use of AR and *(2)* new approaches for context-dependent permission models that give users fine-grained control over AR sensor usage.

Privacy risks with AR interfaces: The security & privacy community is exploring novel privacy risks posed by AR interfaces through empirical studies with prospective users [4, 19, 26] and investigations into the vulnerabilities of current AR ecosystems [12, 13, 68]. Aligned with Guzman et al.'s data-centric threat model [18], our work considers how privacy risks can arise from data flows between the physical environment, AR operating systems, AR apps, and users' interactions with AR apps or other individuals.

End-users' primary concerns with AR input and data processing stem from the capture of biometric data [26, 57], which can enable identifying users from limited amounts of motion data and gesture patterns [50, 53] or inferring sensitive details about their physical surroundings, health status, and personal preferences [3, 4, 42, 49]. AR environmental tracking also raises bystander privacy concerns, similar to lifelogging devices [32, 39], but these concerns may be heightened by AR devices' combination of sensors and advanced inference capabilities [61]. Empirical studies show that wearers of these devices are mindful of bystander privacy [9] but have limited mechanisms to provide awareness or request consent from bystanders before using AR devices in their vicinity [19, 57].

AR interaction techniques raise additional challenges for interpersonal privacy. Users may be reluctant to publicly use natural AR interaction modalities, such as gestures and speech, due to concerns with social acceptability or shoulder surfing [27, 69]. Multi-user AR experiences also require fine-grained access control to manage which aspects of physical and digital environments collaborators are allowed to view and manipulate [43, 58, 59, 64].

AR permission models: Ultimately, AR users' perception of privacy risk varies based on their context and personal preferences [26, 55]. To enable AR users to granularly control AR sensing capabilities to meet their dynamic privacy needs, recent systems contribute adaptive permission models that automatically adjust AR apps' access to sensor data based on context-specific policies. Erebus [38] and ContextIoT [35] facilitate permission authoring through natural language rules, e.g., to restrict object detection to specific classes of physical objects, times, and locations. The World-Driven Access Control framework enforces sensing policies at a multi-user scale by linking them to physical locations, e.g., using beacons to automatically disable cameras near restrooms [63].

2.2 Adaptive AR Interfaces

Adaptation of user interfaces has been a key concern in much of the HCI literature [67], and researchers have long articulated that a critical need for AR interfaces to become pervasive is the ability to adapt to the user and environment [28, 44]. Recent advances in XR have led to an increase in adaptive approaches through improved context-aware sensing technologies and a rise of computational interaction approaches [36].

AR Adaptive Approaches: Existing research on adaptive AR has primarily focused on modeling users' physical surroundings and cognitive states in real-time [14, 45]. An early example is SnapToReality [56] which automatically transformed AR widgets to align with real-world geometry. Lindlbauer et al. [45] present a context-aware approach that adjusts interfaces' level of detail [20] based on users' cognitive load. More recent work develops adaptive layouts for collaborative settings [48] and domain-specific applications. For example, AdapTutAR scaffolds learning of instructional machine tasks by monitoring and adjusting the tutorial to users' task progress [33].

AR Adaptation Frameworks: To understand the design space of adaptation operations, Todi & Jonker's framework addresses key questions related to content selection (what and how much), presentation (how and when), and placement (where) [70]. Cho et al. [15] emphasize the challenges with evaluating adaptive XR interfaces, noticing an increase in complexity given the increased number of adaptation opportunities compared to other interactive technologies. While prior work has primarily focused on layout adaptation, some approaches broaden the scope by considering the semantics of physical objects [14], physical ergonomics of the human body [7], and head motion and eye gaze dynamics [46] when adapting interfaces.

Developer Tool Support: We note an increase in developer tool support for adaptive XR interfaces. For example, the Unity MARS[1] authoring tool enables specifying adaptation rules with respect to proxies, which represent real-world objects and their possible states. In research, XSpace [29] enables developers to create multi-user XR experiences optimized for remote collaboration by adapting to users' physical spaces. The AUIT [8] toolkit enables combining multiple ergonomic adaptation objectives, such as visibility and reachability of UI elements, while resolving conflicts between competing objectives and managing transitions between

[1] **Unity MARS:** https://unity.com/products/unity-mars

different adaptation states. While incorporating privacy considerations in adaptation policies is possible in principle, prior HCI systems research has not explicitly studied this.

2.3 The Challenge with Privacy as an Adaptation Objective

Usability and ergonomic adaptation objectives typically have well-defined benchmarks that can be computationally optimized for (e.g., minimizing users' cognitive load [45] or keeping interactable objects within comfortable reach [7]). In contrast, satisfying users' privacy needs does not have a uniform success metric. Individuals' privacy preferences can vary based on their context (e.g., their physical surroundings, task at hand [55]), perceptions towards data types that AR devices collect or compute [26], and how they assess the tradeoffs with usability. These complex, context-dependent factors require developers to provide AR users with a range of adaptation techniques to meet their individual privacy preferences, rather than implementing a one-size-fits-all solution.

However, despite the progress made in AR permission models and privacy-enhancing technologies, it can be challenging to avoid a zero-sum outcome where the core AR functionality is undermined. Privacy By Design [11] calls for functionality to be preserved as far as possible, and HCI researchers are increasingly exploring AR interaction techniques that balance usability and privacy requirements [59]. However, this research remains scarce and scattered across the literature, making it challenging for AR developers to extract actionable guidelines without privacy expertise.

Our goal is to make privacy considerations more explicit to AR developers by demonstrating the range of privacy-oriented adaptation operations and scaffolding their navigation of that design space. Similar to Abraham et al.'s research on UX-based AR permissions [2], we employ a permission model to simulate how limiting access to certain sensing capabilities can result in the loss of key AR functionalities (e.g., gesture recognition, spatial mapping). Then, we explore how these capabilities can still be achieved through adaptations at the user interface level, offering privacy-friendly alternatives without degrading essential AR functionality.

3 Research Approach

A key challenge in our work was structuring the design of AR adaptation techniques to address the multifaceted adaptation objective of privacy. This section walks through our research approach; Figure 1 illustrates how each investigative step informed the next, using the Double Diamond model.

At the core of the paper are two studies. First, we conducted an **elicitation study with 10 AR researchers** to systematically explore the design space of privacy-driven adaptation techniques. This resulted in an *adaptation catalog* of 62 techniques for accomplishing traditional AR functionalities in more privacy-conscious ways. To define the bounds of this design space and structure our analysis, we established two key design considerations: a *permission model* and *adaptation approaches*. These design considerations guided our development of two *elicitation scenarios*–AR usage scenarios implemented as Unity prototypes–which we used to facilitate the study and prompt consideration of usable privacy tradeoffs.

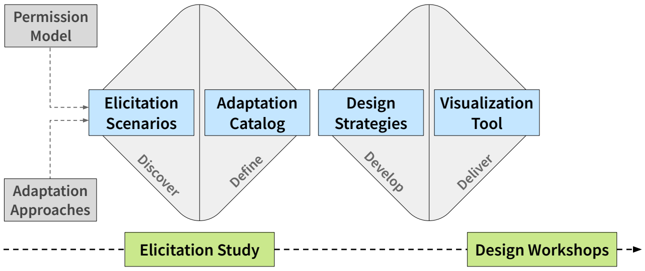


Figure 1: Research Approach. First, we conducted an elicitation study with 10 AR researchers to systematically produce privacy-driven adaptation techniques, yielding an adaptation catalog of 62 techniques. Then, guided by researchers' design strategies, we created a visualization tool to support AR developers in identifying suitable adaptation techniques across the design space. We evaluated the catalog and tool through design workshops with AR developers.

The second stage of our research investigated how to make the adaptation catalog approachable for AR developers without privacy expertise, through **design workshops with six AR developers**. We first analyzed the *design strategies* the 10 AR researchers employed in our elicitation study. Based on these strategies, we created a *visualization tool* that enables filtering, comparing, and viewing suggested implementations for adaptation techniques. During the workshops, the six developers used the tool to identify techniques that address varying personas' privacy goals [21]. Our analysis highlighted the tool's utility for providing clear entry points into the design space, as well as a future need to reduce implementation barriers to encourage adoption of privacy-driven adaptations.

In the rest of this section, we detail the design considerations (Sec. 3.1-3.2) and elicitation scenarios (Sec. 3.3) that guided our elicitation process and analysis of proposals.

3.1 Permission Model

First, we scoped our exploration around a set of AR sensing capabilities from state-of-the-art commercial XR devices (e.g., HoloLens 2, Meta Quest Pro), using the following **AR device specifications:**

- **AR input capabilities:** RGB cameras (used for spatial mapping and head tracking), infrared and depth cameras (used for spatial mapping, hand tracking, and eye-tracking), microphones, and the inertial measurement unit.
- **AR output capabilities:** AR visual output (via a holographic or LCD display), stereo audio, and spatial audio.
- **Other capabilities:** WiFi and Bluetooth.

Then, to consider a wide range of end-users' privacy preferences, we adopted a **permission model** (Fig. 2) that defines the extent to which AR applications can make use of AR sensing capabilities that leverage these input modalities, e.g., spatial mapping or speech recognition. We assume the operating system is a trusted entity and implements this permission model.

(1) **Full access:** this represents the least restrictive permission; there is no change in the quantity or frequency of raw data that the AR app can access.

(2) **Partial access**, including *(a)* making use of limited features within a data stream (e.g., accessing body pose rather than raw camera data); *(b)* limiting data access for specific parties (e.g., allowing access to the app provider but not to other AR users).
(3) **No access:** this is the most restrictive permission level and may result in the loss of core AR functionality (e.g., fully restricting access to RGB cameras would prohibit traditional camera-based tracking methods for marker-based and marker-less AR).

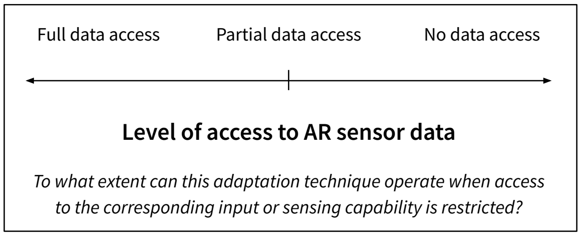

Full data access
Partial data access
No data access
Level of access to AR sensor data
To what extent can this adaptation technique operate when access to the corresponding input or sensing capability is restricted?

Figure 2: Permission Model: Our first design consideration defines AR apps' access to sensor data—ranging from full access to partial access, to no access—representing the least to most privacy-conscious options, respectively.

While prior privacy-focused AR design studies used constrained *threat models* to structure brainstorming [59, 71], we used a *permission model* to capture a wider range of potential privacy threats in our adaptation catalog. For example, a visual-inertial tracking technique that uses sparser frequencies of camera data (i.e., partial data access) could protect both users' privacy in their personal homes and bystanders' privacy in public environments.

3.2 Adaptation Approaches

To characterize the effort required by the system or the user to adapt the AR interface, we defined a second design consideration of **adaptation control**, drawing from foundational literature on context-aware and mixed-initiative interfaces [1, 25, 31]:

(1) **System-driven** adaptation techniques can be automatically applied by the AR app or operating system (e.g., adding noise to raw input data).
(2) **Mixed-initiative** adaptation techniques require a joint effort between the system and the user to enable (e.g., user-guided obfuscation of sensitive environmental features).
(3) **User-driven** adaptation techniques are applied by the AR user, involving manual effort or a change in interaction modalities.

3.3 AR Usage Scenarios for Elicitation

To help participants in our elicitation study envision how to replace or gracefully degrade AR functionality to address various privacy needs, we prototyped two AR usage scenarios inspired by common use cases in the literature: *(1)* an AR Navigation app that a newcomer to a city uses for wayfinding [5, 23], and *(2)* an AR Remote Assistance system employed by factory worker and technical expert to collaboratively troubleshoot equipment failure [24, 41]. To evoke a range of usability and privacy challenges, we designed these scenarios to span multiple AR sensing modalities, single- and multi-user AR interfaces, and public vs. private environments.

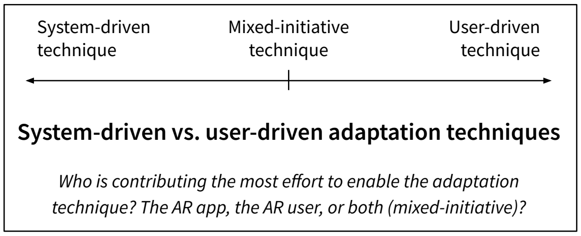

System-driven technique
Mixed-initiative technique
User-driven technique
System-driven vs. user-driven adaptation techniques
Who is contributing the most effort to enable the adaptation technique? The AR app, the AR user, or both (mixed-initiative)?

Figure 3: Adaptation Approaches: Our second design consideration describes whether privacy-driven adaptation techniques can be implemented in a system-driven, user-driven, or mixed-initiative manner.

While prior privacy-focused elicitation studies and design workshops used text-based [10, 40, 71] and image-based depictions [59], we prototyped our scenarios as interactive Unity scenes that demonstrate privacy risks stemming from changes in the physical environment. This approach allowed us to illustrate the "before" and "after" effects of applying sensing restrictions on the user experience, to help our study participants understand the corresponding impact on both usability and privacy.

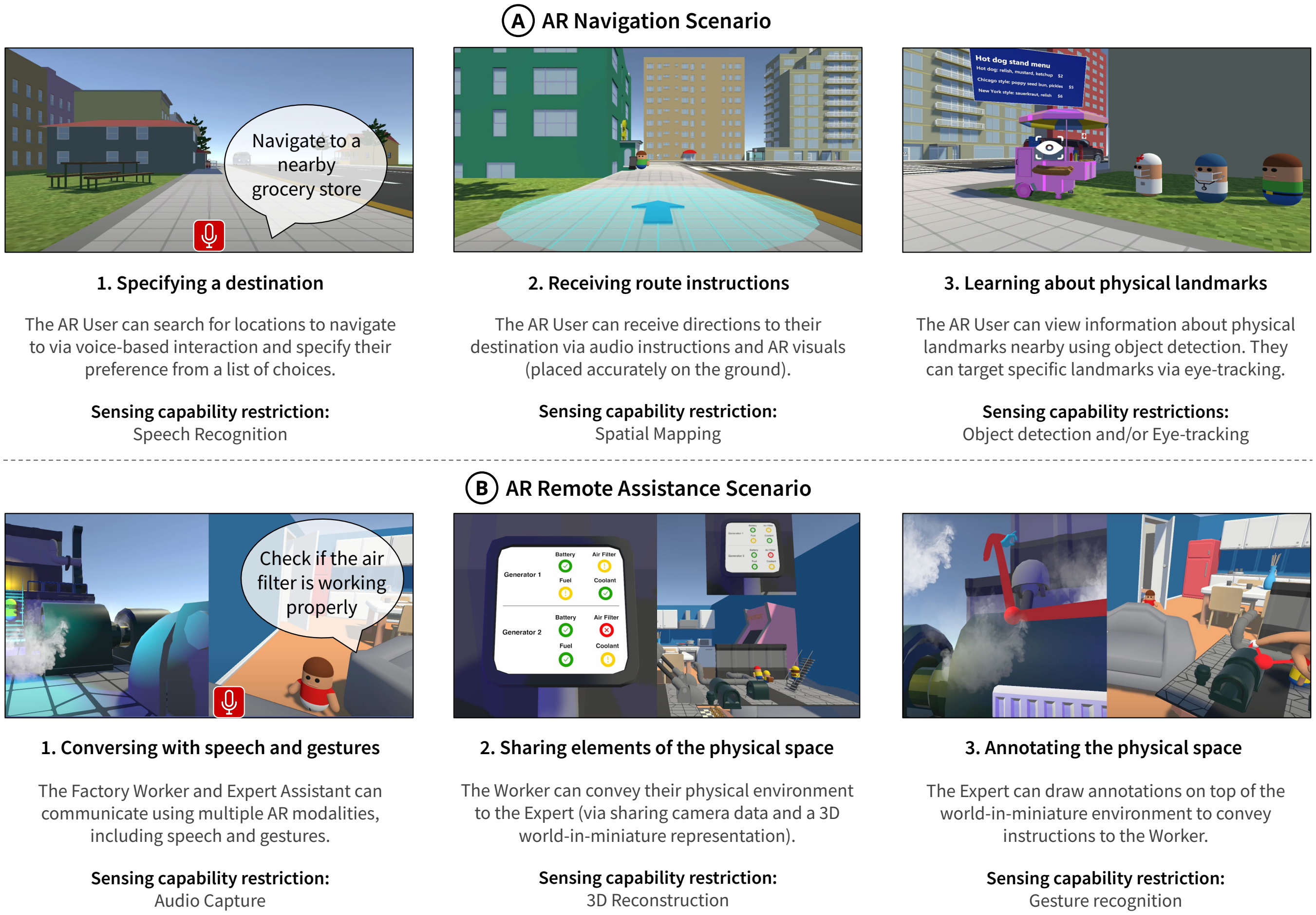
In this section, we describe the interactions we prototyped for each scenario and the AR sensing restrictions imposed to elicit privacy-driven adaptation techniques along the permission model.

AR Navigation (Single-User Scenario). Our first scenario involves a new resident in a city using AR to find their way to different locations and learn information about the area (Fig. 4A).

(1) **Specifying a destination:** The user utilizes voice-based interaction to search for locations and specify their preference from a list of choices. We **restricted speech recognition** capabilities to highlight the benefits of voice input for hands-free navigation (e.g., allowing the user to focus on the road), while contrasting it with privacy concerns (e.g., bystanders potentially overhearing the user's intended destinations).
(2) **Receiving route instructions:** The user receives directions to their destination via audio and AR visuals (placed accurately on the ground). For this interaction, we elicited techniques to enable tracking and registration of virtual content while **restricting access to spatial mapping**.
(3) **Receiving information about physical landmarks:** The user views information about nearby physical locations using object detection, specifying landmarks to target via eye-tracking. We **restricted object detection and eye-tracking permissions**, as this is a popular combination of modalities to enable natural and implicit interactions, but are considered more privacy-invasive than other AR data types [26].

AR Remote Assistance (Multi-User Scenario). Next, we prototyped an AR telepresence application similar to Microsoft's Dynamics 365 Remote Assist[2] and Vuforia Chalk[3] (Fig. 4B). There are 2 main users: a Factory Worker, located at the factory and seeking help to resolve an issue with a generator, and a Technical Expert, located in their personal home and instructing the Worker to solve the issue.

[2] **Dynamics 365:** https://dynamics.microsoft.com/en-us/mixed-reality/remote-assist/
[3] **Vuforia Chalk:** https://www.ptc.com/en/products/vuforia/vuforia-chalk


Navigate to a nearby grocery store
Hot dog stand menu
Hot dog: relish, mustard, ketchup $2
Chicago style: poppy seed bun, pickles $5
New York style: sauerkraut, relish $6
Check if the air filter is working properly
Generator 1
Battery
Air Filter
Fuel
Coolant
Generator 2
Battery
Air Filter
Fuel
Coolant

Ⓐ AR Navigation Scenario

1. Specifying a destination

The AR User can search for locations to navigate to via voice-based interaction and specify their preference from a list of choices.

Sensing capability restriction:
Speech Recognition

2. Receiving route instructions

The AR User can receive directions to their destination via audio instructions and AR visuals (placed accurately on the ground).

Sensing capability restriction:
Spatial Mapping

3. Learning about physical landmarks

The AR User can view information about physical landmarks nearby using object detection. They can target specific landmarks via eye-tracking.

Sensing capability restrictions:
Object detection and/or Eye-tracking

Ⓑ AR Remote Assistance Scenario

1. Conversing with speech and gestures

The Factory Worker and Expert Assistant can communicate using multiple AR modalities, including speech and gestures.

Sensing capability restriction:
Audio Capture

2. Sharing elements of the physical space

The Worker can convey their physical environment to the Expert (via sharing camera data and a 3D world-in-miniature representation).

Sensing capability restriction:
3D Reconstruction

3. Annotating the physical space

The Expert can draw annotations on top of the world-in-miniature environment to convey instructions to the Worker.

Sensing capability restriction:
Gesture recognition

Figure 4: Elicitation Scenarios. Our AR NAVIGATION scenario involves a new resident leveraging AR to wayfind in a new city. After specifying a destination *(A1)*, they receive in-situ route directions via AR visuals *(A2)* and can target physical landmarks to learn more about *(A3)*. In the AR REMOTE ASSISTANCE scenario, a Factory Worker seeks help with a broken generator. A Technical Expert provides guidance through speech and gestures *(B1)*, observes a live 3D reconstruction of the factory *(B2)*, and annotates the reconstruction to demonstrate troubleshooting steps *(B3)*.

(1) **Conversing with speech and gestures:** the Worker and Expert communicate using speech and gestures. We **restricted the Expert's audio capture permissions** to create a tension between using speech as a natural communication modality and the privacy risks it poses to bystanders in the Expert's personal home.
(2) **Sharing elements of the physical space:** the Worker conveys their physical environment to the Expert through first-person video and a 3D world-in-miniature representation to aid in troubleshooting the issue. To investigate methods for conveying spatial detail using coarser-grained approaches or alternative sensing techniques, we **restricted the Worker's 3D reconstruction permissions**.
(3) **Annotating elements of the physical space:** the Expert draws annotations on top of the world-in-miniature environment to convey instructions to the Worker. Here, we **restricted the Expert's permissions for gesture recognition** to explore how gestures, which are perceived as less privacy-invasive compared to speech [26], could still pose subtle privacy risks (e.g., inferring health conditions or gender from hand size).

4 Elicitation Study

The first key contribution of our research is a design space exploration of privacy-driven adaptation techniques for AR interfaces. To systematically structure this exploration, we conducted a scenario-based elicitation study [51, 59, 72] with 10 AR researchers. Our goal was to develop an adaptation catalog that reflected diverse user privacy preferences. As such, we guided participants to produce techniques spanning system- to user-driven control (Sec. 3.2) and varying levels of sensing access within the permission model (Sec. 3.1). This approach allowed us to balance usability and privacy goals, rather than only prioritizing the most privacy-preserving techniques.

AR Researchers				
Participant ID	**Job Role**	**Areas of Expertise**	**Expertise in Adaptive AR**	**Expertise in Privacy**
AR1	Research scientist	collaborative and asymmetric XR interfaces		
AR2	Research scientist	XR interaction techniques	✓	
AR3	PhD student	AI-driven and context-aware AR interfaces	✓	
AR4	PhD student	adaptive AR interfaces	✓	
AR5	Research scientist	XR interaction techniques	✓	
AR6	PhD student	sensing techniques for IoT, XR		✓
AR7	Postdoctoral researcher	collaborative XR interfaces, usable security & privacy	✓	✓
AR8	Assistant Professor	collaborative XR interfaces, safety and ethics for XR		✓
AR9	Postdoctoral researcher	XR interaction techniques	✓	
AR10	Postdoctoral researcher	AR learning experiences		

Table 1: Participant information. We recruited 10 researchers with 2+ years of AR development experience and at least 2 first-authored publications that required developing functional AR/VR prototypes. 6 out of 10 researchers also had prior experience developing adaptive AR interfaces; 3 out of 10 have prior research publications on privacy-related topics.

4.1 Participants

Based on recent CHI and UIST publications, we identified and recruited AR researchers with at least two years of AR development experience and two first-authored AR/VR systems research papers. To encourage creative adaptation technique proposals, we focused on HCI researchers active in CHI and UIST to ensure a diverse participant pool (e.g., expertise in parallel domains such as IoT and the ability to think critically about privacy and ethics). 10 researchers participated in our study (average age of 31.5 years, 1 female, 5 male, 4 declined to answer). Table 1 shows an overview of the researchers' job roles and areas of expertise. All researchers reported having significant experience in 3D, AR, and VR interaction design. 6 out of 10 researchers also had experience developing adaptive AR/VR interfaces. 3 out of 10 previously conducted research in AR and usable privacy; all other researchers reported limited experience with privacy & security topics.

4.2 Method

We conducted individual, 1-hr study sessions with the 10 AR researchers over Zoom. The study consisted of three phases: *(1)* an introduction to privacy-driven AR adaptation techniques, *(2)* an elicitation task where the researchers produced adaptation technique proposals with respect to our two scenarios, and *(3)* a discussion on their design strategies. Participants were compensated with a $50 USD gift card for completing the elicitation study and a follow-up survey to provide feedback on the full adaptation catalog.

Study Introduction *(5 min)*: We first introduced the concept of privacy as an adaptation objective, our permission model, and the AR device specifications under assumption (Sec. 3.1). We allowed the researchers to define additional device capabilities as needed (e.g., external sensors or hardware).

Elicitation Task *(20 min per scenario)*: The core of the study was an elicitation task, where the researchers designed adaptation techniques for the key user interactions in the AR Navigation and AR Remote Assistance scenarios. We used our Unity prototypes to demonstrate the scenarios, using animation sequences to depict the interactions and changes in the environment (e.g., bystanders entering the users' FOV). Participants could directly manipulate the prototypes to better understand usable privacy considerations, e.g., by taking the perspective of different characters [60].

To demonstrate AR interactions, we first simulated the original functionality, assuming full permissions for all sensing capabilities. Then, we showed how each interaction would change if the user fully restricted access to these capabilities. For example, for the *Sharing elements of the physical space* interaction in the AR Remote Assistance scenario, the prototype first shows the Technical Expert viewing an AR world-in-miniature (WIM) of the factory and a first-person camera feed from the Worker's AR headset (Fig. 4B.2). When the Worker restricts access to 3D reconstruction, the WIM is hidden. By contrasting the ideal AR functionality with a privacy-friendly but significantly less usable interaction, we highlighted the need for better adaptation techniques.

For each key interaction, we asked the researchers to produce 2-3 adaptation technique proposals using the following prompt: "If we restrict access to [sensing capability], how could you adapt or redesign the AR interface to still achieve [key interaction]?" Here, we used production as a strategy to reduce legacy bias and cover a wider area of the design space [52]. For the first interaction in the AR Navigation scenario, we demonstrated one example of an adaptation technique to scaffold the researchers' design process: typing via mid-air gestures to specify a destination, rather than using voice-based interaction.

Using a Miro[4] board, we mapped the techniques along visualizations of the design considerations (similar to Fig. 2-3) to indicate their required level of sensor access and adaptation control. This clarified our understanding of the researchers' proposals and encourage them to cover different areas of the design space.

Discussion *(15 min)*: We ended with a discussion around design strategies that the participants utilized to brainstorm privacy-driven adaptation techniques.

4.3 Data Collection & Analysis

We recorded both screen and audio during each study session for subsequent analysis. To analyze the 177 adaptation technique proposals across both scenarios, we applied an affinity diagramming approach [65]. First, one author aggregated similar proposals by reviewing the AR researchers' descriptions of techniques. Next, three authors collaboratively reviewed these clusters, voting on how to merge similar proposals and situate them within the design

[4] **Miro:** https://miro.com/

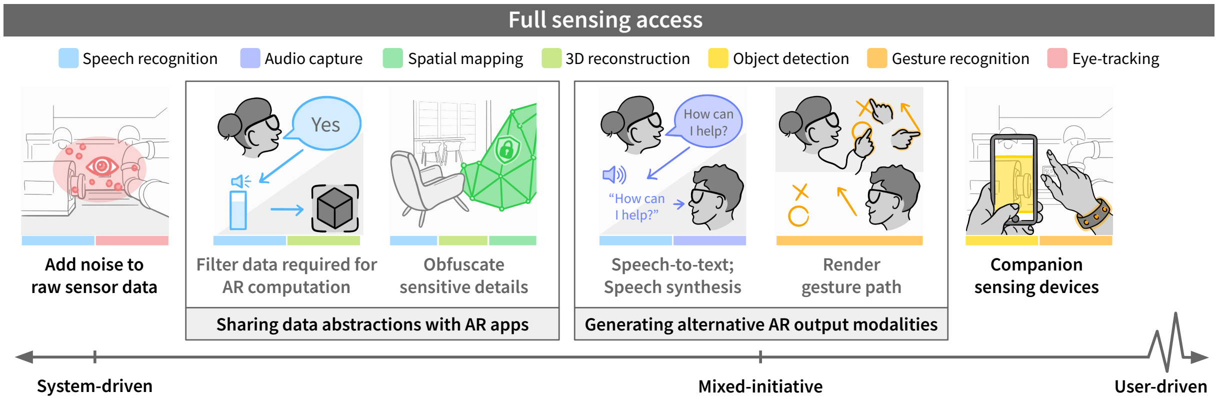

Full sensing access
Speech recognition
Audio capture
Spatial mapping
3D reconstruction
Object detection
Gesture recognition
Eye-tracking
Yes
How can I help?
"How can I help?"
Add noise to raw sensor data
Filter data required for AR computation
Obfuscate sensitive details
Sharing data abstractions with AR apps
Speech-to-text; Speech synthesis
Render gesture path
Generating alternative AR output modalities
Companion sensing devices
System-driven
Mixed-initiative
User-driven

Figure 5: Privacy-Driven Adaptation Techniques involving Full Data Access. We elicited four classes of system-driven and mixed-initiative techniques (from left to right): adding noise to raw sensor data, sharing data abstractions with AR apps, generating alternative AR output modalities, and using companion sensing devices for body or environmental tracking. The AR experts proposed variations of some techniques across different sensing modalities, as indicated by the colored bars.

space, as defined by our design considerations (Sec. 3.1-3.2). This process resulted in an adaptation catalog of 62 techniques.

We generally retained proposals as separate techniques when study participants had differing opinions about their placement within the design space. For example, we categorized *Toggling spatial mapping capabilities* as two separate adaptation techniques with manual (user-driven) and automatic (system-driven) approaches.

5 Privacy-Driven Adaptation Techniques for AR Interfaces

In this section, we present a catalog of 62 privacy-driven AR adaptation techniques derived from our elicitation study. We begin by characterizing the different classes of techniques across each level of the permission model (Sec. 5.1). Then, we describe three design strategies that emerged to address usable privacy tradeoffs (Sec. 5.2), involving adaptation techniques that: *(1)* spatiotemporally degrade AR sensing to maintain continuity in the user experience while respecting bystander privacy; *(2)* infer restricted sensor data using privacy-friendly "proxies;" *(3)* generate AR content to support multi-user interactions that individual users' privacy permissions prevent from being directly achieved.

5.1 Adaptation Techniques Spanning the Permission Model

Figures 5-7 illustrate the adaptation techniques designed by the AR researchers to address the entire range of permission levels: full, partial, or no access to specific sensing capabilities. Appendix A includes descriptions of techniques, organized by modality.

AR researchers proposed the greatest quantity and variety of techniques for the intermediate level of the permission model, where AR apps have partial access to specific sensing capabilities (30 techniques), followed by no access (20) and full access (12). 29 techniques were categorized as system-driven, 16 as mixed initiative, and 17 as user-driven. Speech Recognition and Audio Capture accounted for the highest frequency of techniques (11 each), followed by Gesture Recognition (10), Spatial Mapping and 3D Reconstruction (9 each), Object Detection (7), Eye-Tracking (5).

Full Sensing Access *(12 techniques).* To support user privacy without imposing AR sensing restrictions at the OS level, researchers proposed four classes of techniques (Fig. 5). We describe these techniques ranging from the most system-driven to mixed-initiative, with no techniques categorized as user-driven.

(1) **Adding noise to raw sensor data** to obscure users' biometric input, such as for eye-tracking or voice data (e.g., via voice modulation). While researchers acknowledged potential usability tradeoffs, such as reduced tracking accuracy or sense of immersion, they recommended employing state-of-the-art methods (e.g., differential privacy [22, 54]) to minimize adverse impacts.
(2) **Sharing data abstractions with AR apps** to limit AR apps' access to only the data required to enable core functionality. Researchers' proposals included using OS-level recognizers [34] to filter voice keywords and depth features, rather than passing raw audio or camera streams to AR apps. Additionally, sensitive details, such as specific areas of the physical environment or background noise, can be obfuscated to prevent passive capture of bystanders (e.g., via models trained to remove personally identifiable information such as Project Aria's EgoBlur[5]).
(3) **Generating alternative AR output modalities** to support multi-user interactions when the preferred output format is restricted by individual users' privacy permissions. Proposals included converting speech-to-text, using speech synthesis, or rendering gesture paths instead of users' hand geometry to minimize exposure of their biometric data to collaborators.
(4) **Using companion sensing devices to compute AR interaction data**, e.g., wristbands for gesture recognition [73] or mobile phones for camera-based object tracking. AR6 noted that distributing functionality across companion devices, rather than relying on a single AR device for environmental or body tracking, could enhance user agency by enabling easier decoupling of components.

[5] **EgoBlur:** https://arxiv.org/abs/2308.13093

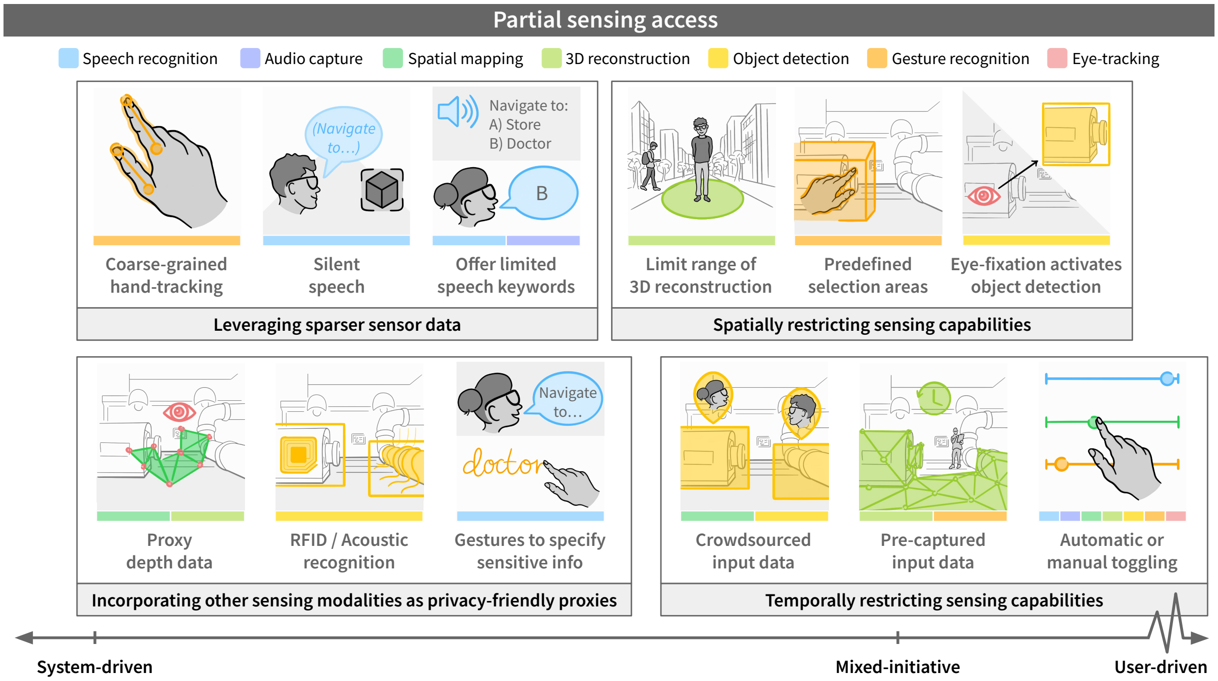

Partial sensing access
Speech recognition
Audio capture
Spatial mapping
3D reconstruction
Object detection
Gesture recognition
Eye-tracking
(Navigate to...)
Navigate to: A) Store B) Doctor
B
Coarse-grained hand-tracking
Silent speech
Offer limited speech keywords
Leveraging sparser sensor data
Limit range of 3D reconstruction
Predefined selection areas
Eye-fixation activates object detection
Spatially restricting sensing capabilities
Navigate to...
doctor
Proxy depth data
RFID / Acoustic recognition
Gestures to specify sensitive info
Incorporating other sensing modalities as privacy-friendly proxies
Crowdsourced input data
Pre-captured input data
Automatic or manual toggling
Temporally restricting sensing capabilities
System-driven
Mixed-initiative
User-driven

Figure 6: Privacy-Driven Adaptation Techniques involving Partial Data Access. We elicited four classes of techniques spanning all levels of adaptation control: leveraging sparser sensor data to reduce capture of biometric data, using privacy-friendly sensing modalities to infer "proxy" data, and spatially and temporally restricting sensing capabilities.

Partial Sensing Access *(30 techniques).* : Next, we identified four classes of techniques to adapt to a limited quantity or degraded quality of AR sensor data. This included 13 system-driven, 10 mixed-initiative, and 7 user-driven techniques (all for manually toggling the 7 sensing modalities we explored). We describe these techniques from the most system-driven to user-driven (Fig. 6).

(1) **Incorporating other sensing modalities as privacy-friendly proxies** for traditional, but potentially privacy-invasive, modalities. Researchers proposed computing proxy depth sensor data (e.g., via optical flow-based estimations from camera streams [41] or using 3D gaze data to create sparse 3D reconstructions [30]), employing RFID or acoustic object recognition instead of camera-based approaches, and switching to gestures to specify sensitive information when voice is the primary modality.
(2) **Leveraging sparser sensor data** to minimize biometric data capture. Examples include performing coarse-grained hand-tracking (e.g., tracking fewer fingers or joints), detecting silent speech [37, 69], and inferring users' intent from limited speech keywords (e.g., selecting option "A" or "B", instead of issuing a full voice command).
(3) **Spatially restricting sensing capabilities**, through area-based approaches (e.g., limiting the range of 3D reconstruction to a small radius around the user, predefining selection areas for gesture recognition) and directional techniques (e.g., eye-fixation to activate object detection).
(4) **Temporally restricting sensing capabilities** by using crowdsourced or precaptured data (e.g., in place of live 3D reconstruction or object detection) or toggling sensing on and off, either automatically or manually (spanning system- and user-driven control). These techniques were viewed as beneficial not only for limiting AR apps' access to sensitive user data but also for preventing the passive capture of bystanders (AR2, 5-6, 10).

No Sensing Access *(20 techniques)*: Finally, researchers proposed leveraging alternative AR input and output modalities to maintain functionality when a sensing capability is fully restricted (Fig. 7). All output techniques were classified as system-driven (4), while the 16 input techniques ranged from system- to user-driven.

(1) **Alternative AR output techniques** to deliver AR content in new ways when sensing restrictions prevent anchoring content in the real-world. Researchers proposed using 2D environment representations (e.g., head-locked visual displays instead of world-anchored ones, 2D floorplans, or RGB video for localization) or conveying AR visuals through audio-haptic cues.
(2) **Alternative AR input techniques** that allow users to completely bypass traditional input methods if they perceive a high privacy risk with those modalities. System-driven and mixed-initiative proposals included estimating proxy eye-tracking data from head orientation and object detection, using voice or eye-tracking to generate gestures, and offering alternative audio input (e.g., scratching on headsets to indicate yes or no). User-driven approaches included typing, selecting options on AR GUIs, gesture-based demonstrations as alternatives to speech, and using voice or gestures as alternatives to eye-tracking.

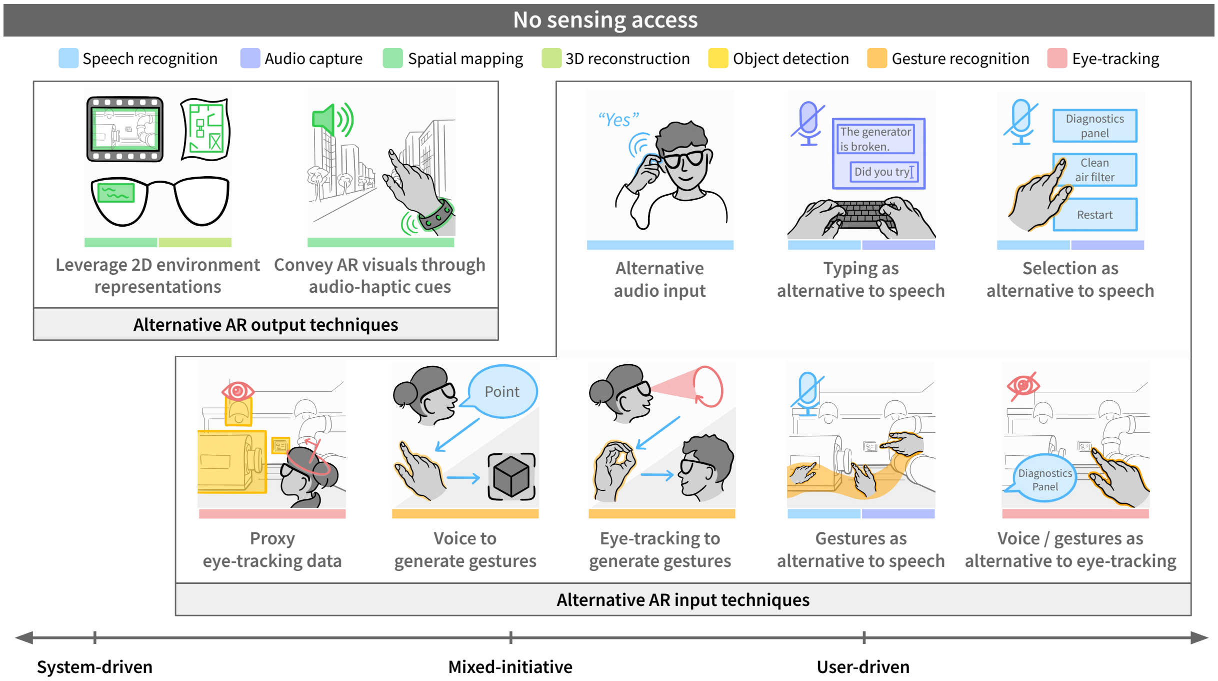

No sensing access
Speech recognition
Audio capture
Spatial mapping
3D reconstruction
Object detection
Gesture recognition
Eye-tracking
Leverage 2D environment representations
Convey AR visuals through audio-haptic cues
Alternative AR output techniques
"Yes"
Alternative audio input
The generator is broken.
Did you try
Typing as alternative to speech
Diagnostics panel
Clean air filter
Restart
Selection as alternative to speech
Proxy eye-tracking data
Point
Voice to generate gestures
Eye-tracking to generate gestures
Gestures as alternative to speech
Diagnostics Panel
Voice / gestures as alternative to eye-tracking
Alternative AR input techniques
System-driven
Mixed-initiative
User-driven

Figure 7: Privacy-Driven Adaptation Techniques involving No Data Access. Researchers proposed system-driven techniques leveraging alternatives to world-anchored AR content under spatial mapping restrictions. They also proposed alternative AR input techniques to give users choices when they perceive privacy risks with traditional AR input, ranging from system- to user-driven approaches.

5.2 Design Strategies: Spatiotemporal Restrictions, Inference & Generation

Our adaptation catalog provides an avenue for AR developers to analyze their AR interaction techniques and identify privacy-friendlier alternatives, considering different levels of sensing access and system- vs. user-driven approaches. However, our discussions with the AR researchers revealed that selecting suitable adaptation techniques for a given context is a complex task, as each technique presents unique usability and privacy tradeoffs. Our analysis surfaced three design strategies that they utilized to balance these tradeoffs, presented with representative examples from our studies.

Design Strategy 1: Spatiotemporal Sensing Restrictions that Maintain Continuity of AR Experiences. In our Navigation scenario (Fig. 4A), always-on sensing (i.e., eye-tracking, object detection, and spatial mapping) allows users to discover new interaction opportunities, such as learning about nearby landmarks. However, this poses significant privacy risks to bystanders who may lack awareness and mechanisms to opt out of data capture. Spatiotemporal sensing restrictions—**limiting the spatial range or active time period of sensing capabilities based on context**—emerged as a strategy to gracefully degrade AR functionality when the user can afford a diminished user experience.

For example, AR3 proposed *Toggling* spatial mapping capabilities and expanding the spatial range when the system detects that the Navigation user is confused, based on their motion or eye-tracking patterns. Similarly, AR4 suggested using *Eye-fixation to activate object detection* when users gaze on an area of interest. These adaptation techniques can minimize capture of bystanders by introducing an intermediate step: using shorter-range sensors like eye-tracking cameras and the IMU to activate longer-range sensors such as cameras and depth sensors.

Design Strategy 2: Privacy-Friendlier Inference via Proxy Data. Certain privacy-driven sensing restrictions can significantly impair or completely halt AR functionality. For example, fully restricting spatial mapping in the Navigation scenario prevents fine-grained localization of the user and spatially registering AR content, reducing the AR device to a heads-up display. In these cases, the AR researchers brainstormed ways to **infer the desired data from another sensing modality**, or, as AR8 described, "how [to] get the same out of another." This approach can be effective when users perceive higher risks with a particular AR sensing modality [26] but remain comfortable with the interactions it enables.

For example, AR8 proposed estimating *Proxy eye-tracking data* through the Navigation user's orientation and saliency maps of the environment, accommodating users who want the system to interpret their gaze but prefer not to use eye-tracking. However, if the user perceives a risk in the system inferring their gaze patterns, this technique could violate their privacy preferences. As such, the researchers emphasized the importance of informed consent and providing users with fine-grained control over the inference method (AR3-4, 6, 9). Some argued that proxy data would only be in service of users' privacy needs if it could be computed with fewer or less privacy-invasive sensors (AR8-9).

Design Strategy 3: Output Generation to Reconcile Individual Privacy Preferences in Multi-User AR. A third usable privacy tradeoff identified in our elicitation study was specific to multi-user AR: individuals' privacy preferences and corresponding adaptations have the potential to degrade the user experience for others AR users. For example, in the REMOTE ASSISTANCE scenario, the Technical Expert might switch from speech to text-based chat to protect their privacy when their child is nearby. However, this adaptation disrupts the Factory Worker's troubleshooting process, as they would lose the ability to receive and respond to instructions in a hands- and eyes-free manner.

To maintain collaboration and communication cues for other AR users, researchers adopted a design strategy of **generating or simulating the desired output modality when permission settings prevent direct access to the required sensing capabilities**. For example, *Speech synthesis* could support interpersonal and bystander privacy by filtering out background sounds, such as the Expert's child, while using AI-generated speech to maintain conversation flow with the Worker (AR6,9). This could be extended with *Generated gestures* to illustrate actions based on the Expert's spoken instructions (AR3-5, 8-10). While participants noted potentially negative impacts on immersion (e.g., AI-generated voices feeling less realistic), this approach offers the benefit of decoupling individual privacy-driven adaptations to balance usability and privacy needs of multiple users, even when those needs are in conflict.

6 Visualization Tool

Our elicitation study takes an important first step in establishing a design space of privacy-driven AR adaptation techniques (Sec. 5.1) and identifying design strategies utilized by the AR researchers to balance usability and privacy goals (Sec. 5.2). However, despite privacy being a widely-recognized need for everyday AR interfaces, many design and development teams still lack the expertise to effectively implement privacy-preserving techniques.

To make our adaptation catalog and overarching design space more approachable for AR developers without formal privacy training, our work also contributes the design and evaluation of a visualization tool (Fig. 8). The tool integrates our design considerations (Sec. 3.1-3.2) and researchers' design strategies into faceted search tools, enabling developers to weigh the usability and privacy implications of different techniques. Our implementation is inspired by community-driven tools that visualize taxonomies of HCI systems research, such as Locomotion Vault [47] and Haptipedia [66].

This section describes the visualization interface and preliminary studies with AR and security & privacy experts to refine the interface. Later, we report on more in-depth design workshops to evaluate the utility of the visualization tool in guiding AR developers to navigate the design space.

6.1 Visualization Tool Interface

Figure 8 shows the user interface of our visualization tool. The **center panel of visualizations** organizes the adaptation techniques from our catalog along the two design considerations: the permission model (A) and level of adaptation control (B). To lower the barrier for AR developers without privacy expertise, we reframed the permission model to highlight its impact on core AR sensing capabilities, categorizing each adaptation technique as fully, partially, or not utilizing these capabilities. Each technique is color-coded by its corresponding AR sensing modality.

We developed a third visualization mapping the input modalities required to enable the adaptation techniques to the corresponding types of output produced (C). Inspired by the techniques that leverage or generate data of alternate AR modalities, the visualization serves two purposes. First, it helps assess implementation needs by highlighting I/O requirements, allowing developers to quickly rule out techniques not supported by their target device. Second, it contrasts privacy-driven adaptation techniques with traditional AR interaction design, enabling developers to weigh the impact on user experience. For example, using *Text-to-speech* to converse in our REMOTE ASSISTANCE scenario could feel cumbersome, whereas *Speech recognition to speech synthesis* enables natural conversation while obscuring the details of users' voices.

To help developers focus on a subset of the design space, we developed a **faceted search interface** with three types of filters (D). First, the *Sensing Restriction* filter allows users to focus on specific modalities, such as viewing techniques for adapting spatial mapping capabilities. Next, we include filters for *Inference vs. Generation* and *Spatial vs. Temporal* restrictions, which align with AR researchers' design strategies. Finally, we enable filtering based on *Input and Output* modalities. Users can select multiple techniques through the brushing functionality and visualize how frequently each adaptation technique was proposed (with more frequent proposals rendered in darker colors).

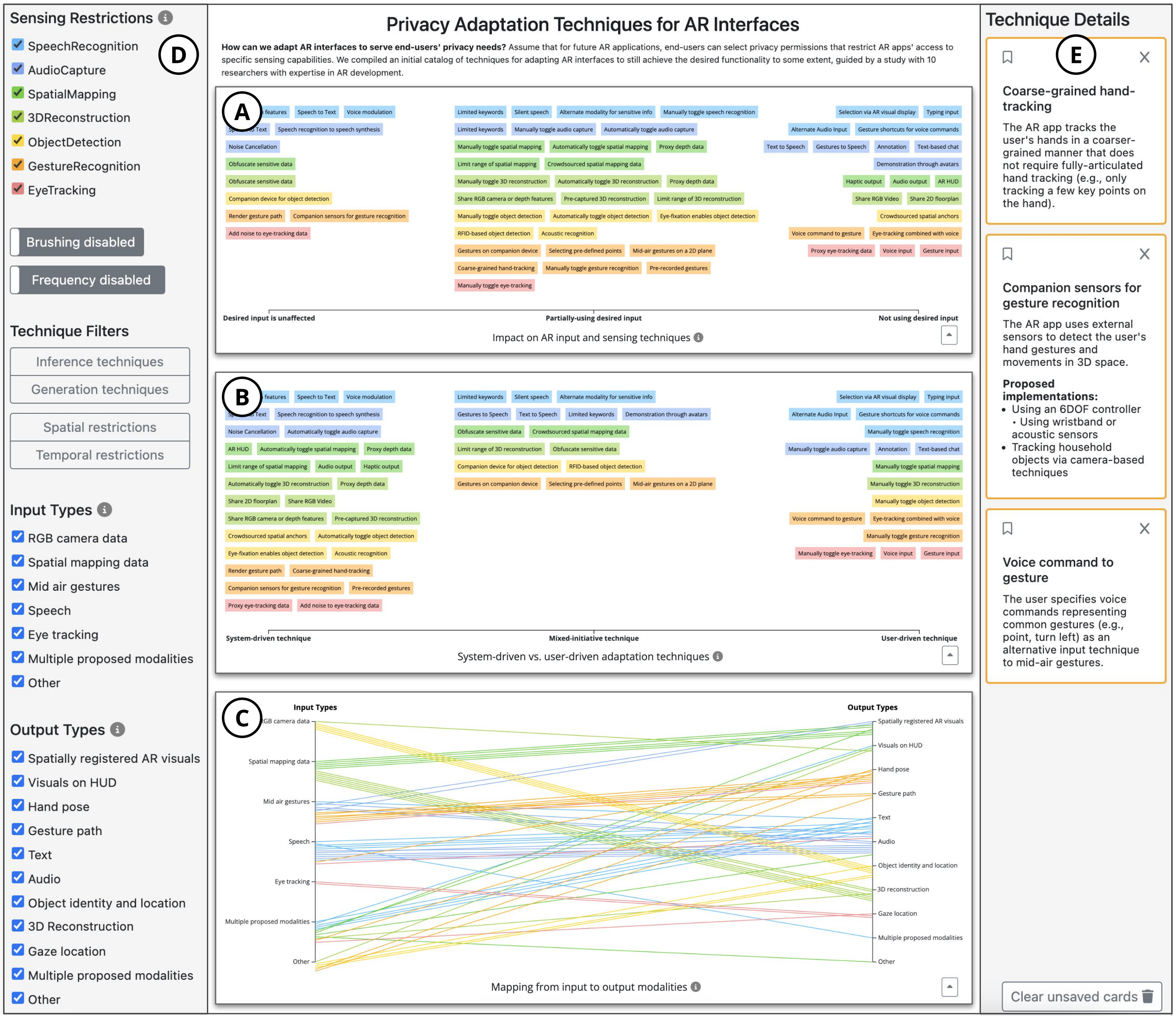
Clicking on a technique populates a card in the **technique details panel** (E), which summarizes the technique and describes possible implementations proposed by the AR researchers. For example, for the *Proxy depth data* technique, the researchers referenced TransceiVR [41] and Hirzle et al.'s implementation of inferring sparse point clouds through the user's 3D gaze data [30].

We implemented the visualization tool as a web interface using HTML, JavaScript, and the Bootstrap framework for styling. We developed the visualizations via the D3.js library[6]. Further information on the visualization tool can be found at https://www.mi2lab.com/research/ar-privacy-adaptations/.

6.2 Review with AR and Security & Privacy Experts

For a preliminary assessment of the visualization tool's usability and utility, we re-engaged 7 of the 10 AR researchers from our elicitation study through asynchronous sessions. To gain a more critical perspective on the privacy considerations of adaptation techniques, we also recruited 3 security & privacy (S&P) researchers, each with 3+ years of experience and at least one AR/VR-focused publication, for synchronous Zoom sessions. In all 10 sessions, researchers used the visualization tool to review the catalog and select three adaptation techniques that they found most suitable for our AR NAVIGATION and AR REMOTE ASSISTANCE elicitation scenarios (Sec. 3.3). They also provided feedback via a survey (for asynchronous sessions) or participated in a discussion (for synchronous sessions)

[6] **D3.js:** https://d3js.org/



Privacy Adaptation Techniques for AR Interfaces

How can we adapt AR interfaces to serve end-users' privacy needs? Assume that for future AR applications, end-users can select privacy permissions that restrict AR apps' access to specific sensing capabilities. We compiled an initial catalog of techniques for adapting AR interfaces to still achieve the desired functionality to some extent, guided by a study with 10 researchers with expertise in AR development.

Technique Details

Coarse-grained hand-tracking

The AR app tracks the user's hands in a coarser-grained manner that does not require fully-articulated hand tracking (e.g., only tracking a few key points on the hand).

Companion sensors for gesture recognition

The AR app uses external sensors to detect the user's hand gestures and movements in 3D space.

Proposed implementations:

- Using an 6DOF controller
  - Using wristband or acoustic sensors
- Tracking household objects via camera-based techniques

Voice command to gesture

The user specifies voice commands representing common gestures (e.g., point, turn left) as an alternative input technique to mid-air gestures.

Sensing Restrictions
☑ SpeechRecognition
☑ AudioCapture
☑ SpatialMapping
☑ 3DReconstruction
☑ ObjectDetection
☑ GestureRecognition
☑ EyeTracking
D
Brushing disabled
Frequency disabled
Technique Filters
Inference techniques
Generation techniques
Spatial restrictions
Temporal restrictions
Input Types
☑ RGB camera data
☑ Spatial mapping data
☑ Mid air gestures
☑ Speech
☑ Eye tracking
☑ Multiple proposed modalities
☑ Other
Output Types
☑ Spatially registered AR visuals
☑ Visuals on HUD
☑ Hand pose
☑ Gesture path
☑ Text
☑ Audio
☑ Object identity and location
☑ 3D Reconstruction
☑ Gaze location
☑ Multiple proposed modalities
☑ Other
A
features
Speech to Text
Voice modulation
Limited keywords
Silent speech
Alternate modality for sensitive info
Manually toggle speech recognition
Selection via AR visual display
Typing input
Text
Speech recognition to speech synthesis
Limited keywords
Manually toggle audio capture
Automatically toggle audio capture
Alternate Audio Input
Gesture shortcuts for voice commands
Noise Cancellation
Manually toggle spatial mapping
Automatically toggle spatial mapping
Proxy depth data
Text to Speech
Gestures to Speech
Annotation
Text-based chat
Obfuscate sensitive data
Limit range of spatial mapping
Crowdsourced spatial mapping data
Demonstration through avatars
Obfuscate sensitive data
Manually toggle 3D reconstruction
Automatically toggle 3D reconstruction
Proxy depth data
Haptic output
Audio output
AR HUD
Companion device for object detection
Share RGB camera or depth features
Pre-captured 3D reconstruction
Limit range of 3D reconstruction
Share RGB Video
Share 2D floorplan
Render gesture path
Companion sensors for gesture recognition
Manually toggle object detection
Automatically toggle object detection
Eye-fixation enables object detection
Crowdsourced spatial anchors
Add noise to eye-tracking data
RFID-based object detection
Acoustic recognition
Voice command to gesture
Eye-tracking combined with voice
Gestures on companion device
Selecting pre-defined points
Mid-air gestures on a 2D plane
Proxy eye-tracking data
Voice input
Gesture input
Coarse-grained hand-tracking
Manually toggle gesture recognition
Pre-recorded gestures
Manually toggle eye-tracking
Desired input is unaffected
Partially-using desired input
Not using desired input
Impact on AR input and sensing techniques
B
features
Speech to Text
Voice modulation
Limited keywords
Silent speech
Alternate modality for sensitive info
Selection via AR visual display
Typing input
Text
Speech recognition to speech synthesis
Gestures to Speech
Text to Speech
Limited keywords
Demonstration through avatars
Alternate Audio Input
Gesture shortcuts for voice commands
Noise Cancellation
Automatically toggle audio capture
Obfuscate sensitive data
Crowdsourced spatial mapping data
Manually toggle speech recognition
AR HUD
Automatically toggle spatial mapping
Proxy depth data
Limit range of 3D reconstruction
Obfuscate sensitive data
Manually toggle audio capture
Annotation
Text-based chat
Limit range of spatial mapping
Audio output
Haptic output
Companion device for object detection
RFID-based object detection
Manually toggle spatial mapping
Automatically toggle 3D reconstruction
Proxy depth data
Gestures on companion device
Selecting pre-defined points
Mid-air gestures on a 2D plane
Manually toggle 3D reconstruction
Share 2D floorplan
Share RGB Video
Manually toggle object detection
Share RGB camera or depth features
Pre-captured 3D reconstruction
Voice command to gesture
Eye-tracking combined with voice
Crowdsourced spatial anchors
Automatically toggle object detection
Manually toggle gesture recognition
Eye-fixation enables object detection
Acoustic recognition
Manually toggle eye-tracking
Voice input
Gesture input
Render gesture path
Coarse-grained hand-tracking
Companion sensors for gesture recognition
Pre-recorded gestures
Proxy eye-tracking data
Add noise to eye-tracking data
System-driven technique
Mixed-initiative technique
User-driven technique
System-driven vs. user-driven adaptation techniques
C
Input Types
GB camera data
Spatial mapping data
Mid air gestures
Speech
Eye tracking
Multiple proposed modalities
Other
Output Types
Spatially registered AR visuals
Visuals on HUD
Hand pose
Gesture path
Text
Audio
Object identity and location
3D reconstruction
Gaze location
Multiple proposed modalities
Other
Mapping from input to output modalities
E
Clear unsaved cards

Figure 8: Visualization Tool for Privacy-Driven AR Adaptation Techniques. To enable AR developers to search for adaptation techniques and weigh tradeoffs across usability and privacy factors, we developed a visualization tool that maps techniques across the design considerations related to permission model (A) and adaptation control (B), demonstrate implementation requirements for input and output modalities (C), provides a faceted search interface for filtering techniques (D), and displays a summary of selected techniques (E) together with proposed implementation plans by the ten AR researchers from our study.

regarding the catalog's comprehensiveness and any perceived gaps in the adaptation techniques.

Both the AR and the S&P researchers gave positive feedback on the visualization tool and adaptation catalog. They noted that it "covered everything [they] would have wanted" (AR6) and included "some techniques that [they] didn't even think about" (SP1). SP3 expressed it was "great to see tools like this... especially [to help] developers understand what are some of the available techniques." In preparation for our design workshops (Sec. 7), we implemented minor revisions to the tool based on their feedback, including clarifying technique descriptions and fixing interface bugs.

7 Design Workshops with AR Developers

To assess to what extent our visualization tool supports AR developers without formal privacy training in creating more privacy-focused interactions, we conducted two design workshops with a total of 6 AR developers. Specifically, we aimed to investigate if and how the tool enabled developers to easily navigate the design space and identify techniques aligned with their goals. During the workshops, we observed how the developers used the tool to compare adaptation techniques when designing for an AR educational app, based on a privacy-oriented scenario from prior work [59].

7.1 Participants

We identified and recruited 6 AR developers (D1-6) through local networks and the HoloDevelopers Slack group[7] (average age of 27 years, 1 female, 4 male, 1 declined to answer). All developers reported having at least 3 years of AR development experience and little to no expertise with security & privacy-focused development.

7.2 Method

We conducted two 1-hr design workshops with 3 AR developers each. Each workshop was conducted over Zoom and included:

An introduction to the online visualization tool: Through a brief walk-through video, we described the different components of the visualization interface, without going into any detail about the adaptation techniques.

Two individual think-out-loud tasks: For each task, participants were introduced to a multi-user AR application scenario and a persona whose perspective they were asked to take. They were then asked to think aloud as they used the visualization tool to choose 2-3 adaptation techniques from the perspective of the persona. Participants performed these tasks in individual Zoom breakout rooms.

For Task 1, all participants assumed the perspective of an AR System Designer who aimed to maintain an interaction design consistent with current application, while minimizing development effort. For Task 2, we assigned participants one of three personas:

(1) a Privacy Fundamentalist, whose goal was to interact with the AR application in the most privacy-preserving manner;
(2) an AR Amateur, who is a novice AR user wanting to achieve a balance between usability and privacy in their interactions;
(3) a Bystander-Concerned User, who is cognizant of how their usage of AR in public spaces impacts others' privacy.

These personas were based on prior empirical studies of typical privacy attitudes [21] and were designed to cover varying user and privacy requirements.

Group discussions and a brief interview: After each think aloud task, all participants rejoined the main Zoom room to discuss the adaptation techniques they chose and their rationale. To end the workshop, we conducted brief individual interviews with each participant to gather their feedback about the adaptation catalog and the tool.

7.3 Data Collection and Analysis

We captured screen and audio recordings of the design workshops. Two researchers performed a thematic analysis of both the observations of participant interactions and the transcripts of the conversations. We used an open coding approach, where we double-coded data from two of the participants to resolve inconsistencies and create a final coding scheme, then clustered the data using axial codes to form the themes we report below.

7.4 Results

The catalog provided a comprehensive overview, exposing developers to new techniques. Participants found that the catalog offered a detailed list of techniques, providing a "very good overview of the choices [they] could make" when developing an AR application (D2). Most participants were excited about the catalog's potential as a guide for developers, emphasizing that it helped them discover new ideas and alternative interaction techniques: "It gives me different alternatives that maybe I forgot to think about or maybe that I never think about" (D6).

The visualization tool allowed developers to navigate the design space quickly and effectively. Despite acknowledging that there was a lot of information to consider, participants found the tool allowed them to skim and learn about the different adaptation techniques with ease. In our sessions, most participants first used the filters to narrow the set of possible techniques based on their perceived requirements (i.e., their assigned persona's goals). They took a deeper look at individual techniques once they felt the filters aligned with these goals, noting that this helped make decisions faster. When asked to reflect on this process, D5 mentioned "I think there's a good amount of things to see, so like, once I filter, I feel like what I have left is manageable."

The design considerations enabled developers to evaluate tradeoffs and make informed decisions. Choosing appropriate privacy adaptations requires balancing conflicting usability needs. Our participants mentioned that our visualization tool "is definitely something that [they] would use in [their] work... because we are always analyzing tradeoffs" (D1). Participants expressed the design considerations "could accelerate the decision making process" (D2), as it helped them "learn the impact of the techniques [and] how much would this influence [the] application–either on performance, development difficulties, [or] user experience" (D6).

We observed the developers using the visualizations to estimate development effort. For example, D4 found that the mapping of input to output modalities showed how "if you're limited to certain inputs... you can [work around to]... get a certain output." D5 leveraged the system-driven vs. user-driven visualization, saying, "based on the developer [effort], I would use the ones that are closer to here *<gestures towards the user-driven end of the spectrum>*... so we have to implement less custom stuff."

Without requiring extensive expertise, the tool encouraged developers to be more mindful of privacy concerns and facilitated meaningful discussions. Our participants felt that incorporating such a tool in their workflow would encourage them to take a more privacy-focused approach. D3 expressed "I've never been concerned with privacy in my work. But after I kind of got a gist of what [the tool] is trying to do... I found it very helpful, especially for someone who needs to take this stuff very seriously." D2 mentioned that "previously when I designed [applications] I will automatically enable all the things... it's not a good design because I may turn a lot of useless things on and I may [not give] that proper level of the access. So I feel using the tool here can definitely help me... I could [use it] like a checklist."

[7] **HoloDevelopers Slack Group:** https://holodevelopersslack.azurewebsites.net/

The group discussions in our sessions also showcased how such a tool could facilitate meaningful conversations around privacy-driven AR interaction design. Despite having minimal privacy experience, the visualization tool provided a common ground for participants, enabling them to validate their choices and discuss differing perspectives on techniques' alignment with a given scenario. Participants also saw value in using the tool to facilitate discussions with different stakeholders. For example, D1 envisioned "show[ing] my boss why I'm doing things and why I'm taking different approaches." D4 saw the tool as "something you can take to your end-user and... talk through some of their [privacy] concerns. And it [could] help us pick and choose and narrow down what we want our end product to have."

Lowering the barrier for implementation is key for the adoption of privacy-driven adaptation techniques. While our tool helped the developers identify suitable techniques with little privacy experience, they emphasized the need for up-to-date implementation suggests tailored to the current landscape of AR technologies. They mentioned their implementation choices are heavily influenced by the perceived effort: "There will be a second step for me to verify whether my target platform or devices support [the techniques I chose]" (D2). As such, they anticipated that other developers may hesitate to adopt privacy-focused techniques without a lower technical barrier to entry: "If it becomes a matter of looking how can I implement [a technique] and all those are things that I have to figure out as a developer, maybe I won't bring up then unless someone told me privacy is super important" (D5). Our participants envisioned a future tool with examples and templates for adaptation techniques, as well as data on technique feasibility across AR platforms.

7.5 Study Limitations

We note three main limitations of our elicitation study and design workshops: coverage of the design space due to limitations of the permission model, generalizability of the adaptation techniques towards other AR scenarios, and the need for further validation with privacy experts.

Coverage of the design space: We used a permission model with three data access levels to guide the AR researchers' design processes. This yielded a diverse catalog of 62 adaptation techniques, with 42 agreed upon by multiple participants [52]. However, this coarse-grained permission model may have limited our exploration of techniques distinct to specific sensing modalities. In our pilot studies, we used a more granular permission model based on Android mobile permissions (similar to the Erebus access control framework [38]). For example, we stratified object detection into permissions for pose, texture, and type. However, this level of detail was overwhelming for participants to consider alongside the other constraints (i.e., scenario with key AR interactions and design considerations). Future work could build on our adaptation catalog to increase the specificity of the permission model and identify possible gaps in the existing set of techniques.

Generalizability of adaptation techniques to other usage scenarios: While we designed our scenarios to represent a variety of privacy factors (i.e., single-user vs. multi-user, public vs. private environments), the small number of AR applications we studied around may limit the generalizability of the adaptation techniques to other AR use cases. We see an opportunity to expand the current catalog by applying the researchers' adaptation strategies (e.g., *filtering required features* or *using companion devices*) to design techniques for new scenarios or sensing capabilities (e.g., body tracking). Community sourcing new techniques, similar to Locomotion Vault's model [47], is another promising approach to scale the catalog and keep pace with the rapid evolution of the AR technology landscape.

Study sample: We primarily studied with individuals with AR and holistic HCI expertise, involving a small number of security & privacy experts to review our adaptation catalog and visualization tool (Sec. 6.2). Prior elicitation studies demonstrated that when privacy expertise is not available, guiding AR experts with scenarios and threat models is an effective strategy for producing high-quality design proposals [59]. However, further validation and expansion of the adaptation catalog with privacy experts is an important area for future work. We also note that studying with AR researchers focused on underlying AR technologies, such as displays and tracking (e.g., in the TVCG and ISMAR communities), rather than AR interaction techniques and applications, may have led to different adaptation techniques and design strategies.

8 Discussion

With the end goal of empowering future AR users to manage their privacy needs across dynamic, everyday contexts, this research: *(1)* establishes a design space of privacy-driven adaptation techniques; *(2)* enables AR developers to navigate this design space through the design and evaluation of a visualization tool. We reflect on the broader implications of these contributions for HCI systems research and AR developers. Then, we outline future work needed to bridge the gap between this design space and the implementation of adaptation techniques in code.

Summary and implications of our work: Our elicitation study addresses a crucial gap in the existing landscape of adaptive AR approaches by centering privacy as the adaptation objective. Our scenario-based approach, guided by a permission model, allowed us to surface techniques beyond visual AR interface adaptations from prior work [7, 14, 45] (e.g., approximating AR environmental tracking data through shorter-range sensing modalities to minimize capture of bystanders [30]). Through our analysis of the 10 AR researchers' proposals, we extracted three design strategies used to balance usability and privacy tradeoffs: spatiotemporal sensing restrictions, using privacy-friendlier proxies to estimate sensor data, and generating alternate output formats to reconcile multiple users' privacy preferences. These strategies, encoded in our visualization tool, also showed potential for helping developers weigh implementation effort and technical feasibility.

Our visualization tool, though in its initial stages, has shown promising results in our studies. It allowed six AR developers with limited privacy expertise to understand the design space, gain exposure to unfamiliar techniques, and become more aware of privacy concerns. We also observed its potential to not only help developers identify suitable techniques, but also to serve as a communication tool for conveying design decisions to end-users, designers, and managers. These findings suggest that with continued maintenance and stronger community engagement, the tool could help streamline AR development workflows and facilitate privacy-informed AR interaction design.

Future research directions: Despite this potential, further research is needed to lower the barrier for developers to implement these adaptation techniques in future AR systems. During our design workshops, participants emphasized the need for guidance in developing both unfamiliar and standardized privacy-enhancing techniques. With the increased research interest in adaptive toolkits such as AUIT [8] and tools like XRgonomics [7], which focus on usability and ergonomic objectives, we would find value in similar toolkits dedicated to privacy-driven adaptation techniques. In parallel, recent work develops adaptation approaches for non-visual AR output modalities, e.g., audio techniques that optimize placement and tones for distinguishability [16, 17]. Given the wide range of I/O and interaction modalities covered by our design space, these and other cross-modal optimization strategies represent promising directions for future work.

To make the proposed adaptation techniques practical in everyday AR settings, automated support may be needed to help end-users transition between AR interface configurations and adjust to dynamic privacy needs without explicit user invocation. Users have often limited knowledge of, let alone the capacity to manage, varying privacy risks [6]. We can expect this to be exacerbated in everyday AR with frequent context changes.

Finally, in the spirit of community-driven tools such as Locomotion Vault [47] and Haptipedia [66], we hope that our visualization tool will facilitate ongoing research and development in privacy-aware AR design.

9 Conclusion

In this paper, we explored how to reduce the barrier for AR developers to provide granular privacy controls for end-users, addressing a critical gap in context-aware adaptation approaches. Our work was carried out in two key steps. First, through an elicitation study with 10 AR researchers, we established a design space of privacy-driven adaptation techniques that offer more privacy-friendly ways to achieve core AR functionalities. Second, we developed a visualization tool that allows developers without privacy expertise to navigate this design space, validating the tool's effectiveness through design workshops with AR developers. Our findings show that both the adaptation catalog and the visualization tool enabled developers to efficiently explore the design space, discover and identify appropriate techniques, and engage in meaningful discussions about usable privacy tradeoffs. This work provides a foundation for empowering AR developers to integrate privacy into their designs while maintaining essential functionality.

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A Appendix

AR Adaptation Techniques for Speech Recognition	
Technique	**Description**
Typing input	The AR user types input via an AR keyboard using an alternate input modality to speech.
Selection via AR visual display	The user selects from a list of options on an AR visual display using an alternate input modality to speech.
Gesture shortcuts for voice commands	The user specifies gestures as 'shortcuts' representing sequences of voice commands that they frequently use.
Alternate audio input	Instead of speech, the AR app accepts different forms of audio input as a selection technique (e.g., choosing yes/no by scratching on the headset).
Limited keywords	The AR app offers a smaller subset of accepted keywords for voice-based interaction (e.g., location categories, yes / no).
Silent speech	The user utilizes silent speech techniques that disclose less detail to bystanders (e.g., mouthing words ror speaking while inhaling).
Share speech features	The OS shares an abstraction of the user's speech data with the AR app (e.g., detected words or features instead of the raw audio signal).
Speech to text	The user speaks phrases and the OS synthesizes the speech into text before making it available to the AR app (speech data is not stored).
Voice modulation	The OS locally modulates the user's audio frequency and adds noise, before giving access to the AR app.
Alternate modality for sensitive info	The user only uses voice to specify high-level intents / requests; the AR app offers another input modality to specify private details of the request.
Manually toggle speech recognition	The user decides when to turn speech recognition capabilities on / off.

Table 2: AR Adaptation Techniques for Speech Recognition.

AR Adaptation Techniques for Audio Capture	
Technique	**Description**
Text-based chat	Multiple AR users communicate via typing phrases into a chat (either through an AR keyboard interface or companion device).
Annotation	Multiple AR users communicate via gesture-based annotation as an alternate technique to audio capture.
Gestures to speech	The app generates speech output for other AR users based on one user's gestures (e.g., generating a description of an object that the user points to).
Text to speech	The user types phrases into a chat (through an AR keyboard interface or alternate input device) and the app synthesizes speech output for other AR users.
Limited keywords	The app offers a smaller subset of accepted keywords for voice-based interaction (e.g., yes / no).
Speech to text	The user speaks phrases and the app synthesizes text output for other AR users (shown as AR visuals), to prevent sharing raw audio data.
Speech recognition to speech synthesis	The user speaks phrases and the app produces synthesized speech output for other AR users.
Noise cancellation	The app uses voice recognition to detect the user's voice and filters out other audio data before streaming it to other AR users.
Manually toggling audio capture	The user decides when to mute or unmute themselves; unmuting streams their speech input to other AR users.
Automatically toggling audio capture	The app infers when the user is talking (via voice recognition) and automatically mutes or unmutes their microphone.
Demonstration through avatars	The AR app captures the user's body movements and conveys them to other AR users through animating a virtual avatar, as an alternative to audio capture.

Table 3: AR Adaptation Techniques for Audio Capture.

AR Adaptation Techniques for Spatial Mapping	
Technique	**Description**
AR HUD	The app shows AR visuals on an AR heads-up display as an alternate output technique to spatially-registered visuals.
Manually toggle spatial mapping	The user decides when to turn spatial mapping capabilities on / off.
Automatically toggle spatial mapping	The AR app automatically turns spatial mapping capabilities on / off by inferring the user's needs or privacy preferences.
Proxy depth data	The AR app infers the correct depth to place the AR visuals through combining other sensing capabilities).
Limit range of spatial mapping	The OS only computes spatial maps within a small area around the user (not utilizing the full range of RGB cameras and depth sensors).
Obfuscate spatial data	The user specifies sensitive types of spatial info (e.g., data involving people or identifying text). The AR app obfuscates / erases this information from spatial maps before storing it for later use.
Crowdsourced spatial mapping data	The app places AR visuals based on previously-captured spatial mapping data (contributed by other AR users who visited the same physical locations).
Audio output	The AR app provides audio instructions as an alternative output technique to spatially-registered AR visuals.
Haptic output	The AR app provides haptic feedback through companion devices (e.g., phone, smartwatch) as an alternative output technique to spatially-registered AR visuals.

Table 4: AR Adaptation Techniques for Spatial Mapping.

AR Adaptation Techniques for 3D Reconstruction	
Technique	**Description**
2D floorplan	The AR app shares a 2D birds-eye view of the user's environment with other AR users as an alternative to 3D reconstruction.
RGB video	The AR app shares RGB video data with other AR users as an alternative to sharing a 3D reconstruction representation.
Share RGB camera / depth features	The AR app shares an abstraction of the user's 3D reconstruction data with other AR users (e.g., removing sensitive details, showing untextured depth data or a bounding box).
Manually toggle 3D reconstruction	The user decides when to turn 3D reconstruction capabilities on / off.
Automatically toggling 3D reconstruction	The AR app infers when the user wants to enable or share 3D reconstruction data with other AR users.
Pre-captured 3D reconstruction	The AR app shares a previously captured 3D reconstruction of the user's environment with other AR users, rather than updating the reconstruction in real-time.
Limit range of 3D reconstruction	The OS only conducts 3D reconstruction within a small area around the user (not utilizing the full range of RGB cameras and depth sensors).
Obfuscate sensitive data	The OS blurs or removes 3D reconstruction data involving a pre-defined list of sensitive information (e.g., bystanders) before passing it onto the AR app.
Proxy depth data	The AR app estimates depth data needed for 3D reconstruction through RGB camera or eye-tracking data.

Table 5: AR Adaptation Techniques for 3D Reconstruction.

AR Adaptation Techniques for Object Detection	
Technique	**Description**
Crowdsourced spatial anchors	The AR app places AR visuals based on previously-defined spatial anchors (contributed by other AR users who visited the same physical locations).
Manually toggle object detection	The AR user decides when to turn object detection capabilities on / off.
Automatically toggle object detection	The AR app automatically turns spatial mapping capabilities on / off by inferring the AR user's needs or privacy preferences.
Eye-fixation enables object detection	The AR app only enables object detection when the user's is fixating their gaze on an object (rather than saccadic / rapid eye-movements).
Companion device for object detection	The user uses an external device (e.g., phone) to capture physical objects; the companion app communicates the detected objects to the AR app.
RFID-based object detection	The AR app only detects physical objects instrumented with RFID tags (which encode descriptive information and the location of the object).
Acoustic recognition	The AR app identifies key physical objects through using acoustic recognition techniques to detect unique audio signals that they emit and perform localization.

Table 6: AR Adaptation Techniques for Object Detection.

AR Adaptation Techniques for Gesture Recognition	
Technique	**Description**
Eye-tracking combined with voice	The user issues voice commands to specify the start and end of eye-tracking input, then uses eye-tracking to draw paths (as an alternate input technique to mid-air gestures).
Voice command to gesture	The user specifies voice commands representing common gestures (e.g., point, turn left) as an alternative input technique to mid-air gestures.
Gestures on companion device	The user draws on a mobile device (e.g., phone or tablet) using multi-touch or pen input to define 2D paths (as an alternate input technique to mid-air gestures).
Selecting pre-defined points	The AR app detects the user's hands' intersections with pre-defined points in 3D space (e.g., intersections with specific physical objects) and only conveys gestures occurring in those intersections to other AR users.
Mid-air gestures on a 2D plane	The AR app detects the user's hands' intersections with a 2D plane (e.g., a map interface) and only conveys gestures occurring in those intersections to other AR users.
Render gesture path, not articulated hand	The AR app only renders the 3D path drawn by the user's hands for other AR users and does not convey other gesture recognition features (e.g., specific hand poses).
Coarse-grained hand-tracking	The AR app tracks the user's hands in a coarser-grained manner that does not require fully-articulated hand tracking (e.g., only tracking a few key points on the hand).
Companion sensors for gesture recognition	The AR app uses external sensors to detect the user's hand gestures and movements in 3D space.
Manually toggle gesture recognition	The user decides when to turn gesture recognition capabilities on / off.
Pre-recorded gestures	The AR app shares pre-recorded gestures (as videos or virtual recreations) with other AR users that demonstrate common actions that the user would perform using mid-air gestures.

Table 7: AR Adaptation Techniques for Gesture Recognition.

AR Adaptation Techniques for Eye-Tracking	
Technique	**Description**
Gesture input	The user gestures to target objects, as an alternate input modality to eye-tracking.
Voice input	The user issues voice commands to target objects, as an alternate input modality to eye-tracking.
Proxy eye-tracking data	The AR app infers the user's eye-tracking data and which objects they are looking at (through head pose or GPS in combination with IMU data).
Manually toggle eye-tracking	The user decides when to turn eye-tracking capabilities on / off.
Add noise to eye-tracking data	The OS adds artificial noise when processing the user's raw eye-tracking data to obscure their exact fixation and saccade patterns.

Table 8: AR Adaptation Techniques for Eye-Tracking.