Reality and Beyond: Proxemics as a Lens for Designing Handheld Collaborative Augmented Reality

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Fig. 1. In this work, we explore how users can share perception, deixis, and control of AR content in handheld collaborative AR (HCAR) systems. For example, an AR system can support users in sharing perception with techniques that align with reality such as Basic AR Perception (e.g., looking over the shoulder) or the system can support flexibility by supporting interaction techniques that go beyond aligning with reality such as Perspective Peeking.

Augmented Reality (AR) has shown great potential for supporting co-located collaboration. Yet, it is rarely articulated in the design rationales of AR systems that they promote a certain socio-spatial configuration of the users. Learning from proxemics, we argue that such configurations enable and constrain different co-located spatial behaviors with consequences for collaborative activities. We focus specifically on enabling different collaboration styles via the design of Handheld Collaborative Augmented Reality (HCAR) systems. Drawing upon notions of proxemics, we show how different HCAR designs enable different socio-spatial configurations. Through a design exploration, we demonstrate interaction techniques to expand on the notion of collaborative

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coupling styles by either deliberately designing for aligning with physical reality or going beyond. The main contributions are a proxemics-based conceptual lens and vocabulary for supporting interaction designers in being mindful of the proxemic consequences when developing handheld multi-user AR systems.

CCS Concepts: • Human-centered computing \(\rightarrow\) HCI theory, concepts and models; Interaction techniques.

Additional Key Words and Phrases: augmented reality, collaboration, proxemics, interaction

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1 INTRODUCTION

Augmented Reality (AR) has demonstrated great potential to support co-located collaboration [9]. Due to their widespread availability, handheld devices have become the dominant platform for AR applications and use cases and have been explored in domains such as education, social gaming, design, and architecture [8]. Handheld Collaborative AR (HCAR) systems allow for novel forms of co-located play [6, 22, 52] and can be integrated into classroom environments [27, 41, 47, 48] to support new collaborative learning activities. They can also support new forms of collaborative design and architecture [17, 26, 43], and other domains such as sports [7].

Early research on Augmented Reality has focused on how technology supports collaboration [3, 27, 40] and more recently there has been an increase in research on collaborative AR systems [8, 9]. Although some of this work focuses on technical, usability, and human factor issues, less attention has been paid to the social aspects of collaborative AR [9]. In research on co-located AR, the concept of collaborative AR frequently emerges. However, its interpretation varies widely between different systems. For example, in HyperCubes [10], students collaborate around a single AR device, in the Meta-AR-app [48] each student has their own device at their own table, and in Blocks [17] co-located users each have a device and collaborate to construct shared AR structures. Furthermore, there is a lack of clarity on how the system’s design affects co-located collaboration. There is a need for shared terminology and richer notation styles for co-located AR systems [6, 9, 45].

Collaborative AR systems are often classified using traditional Computer-Supported Cooperative Work (CSCW) classifications, considering dimensions like time, space, symmetry, scenario, and input/output devices [9, 42]. While existing CSCW frameworks address certain terminology and notation challenges in collaborative AR [6, 9, 45], they do not fully capture the specific challenges of co-located collaborative AR [9, 42]. Although previous work has identified different categories of co-located collaboration [44, 50], current AR or spatial collaboration schemes are limited to a fixed one-to-one relationship between interpersonal distances and collaboration styles [44, 50]. Therefore, there is a need to support a better understanding and design of co-located AR collaboration.

Proxemics theory articulates how people use space to enact their intentions toward engaging with co-located others [18] and proxemic interaction [2, 13] have previously been shown to be a useful analytical lens for designing interactive surfaces and spaces, as well as cross-device systems; however, it has not yet been articulated in the area of co-located AR. Proxemics offers a way to investigate how handheld AR systems can be designed to facilitate co-located collaborative interactions and how different designs can have socio-spatial implications for collaborating users.

In this paper, we contextualize proxemics as a conceptual lens to understand how handheld AR systems enable and constrain different socio-spatial configurations [18]. The lens is intended to enable interaction designers to be more aware of the co-located collaboration dynamics for
which they develop their AR systems to support their socio-spatial literacy [29]. In particular, we synthesize a series of proxemic concepts to expand on the notion of Collaborative Coupling Styles [39, 44, 50] for co-located collaborative AR systems. We extend Wells and Houben’s handheld AR collaboration styles for groups [50] by demonstrating that the relationship between coupling styles and device configurations can be many-to-many, and in this way increase flexibility in collaborative AR.

We use the lens of contextualized proxemic concepts to guide a systematic design exploration of collaborative AR interaction techniques. This exploration was facilitated by the design and implementation of a functional handheld multi-user AR prototype, which allows for exploring and experiencing the design space [30]. From this endeavor, we present 10 interaction techniques that span from being aligned with reality to beyond reality (illustrated in Figure 1). Our findings also led us to propose a continuum for designing AR systems that aligns with reality, goes beyond reality, and in between. To further elucidate the application of these techniques, we present two examples of scenarios using an Evaluation by Demonstration approach (Type 1) [30], demonstrating how different interaction techniques can be combined in the prevalent domains of design and education.

With this work, we contribute the following:

- A conceptual lens, which establishes a common vocabulary for comparison and articulation of collaborative AR systems in terms of their proxemic properties.
- A broadening of the design space of interaction techniques for co-located collaborative AR.
- A discussion aimed to develop a nuanced socio-spatial literacy for understanding trade-offs when designing handheld AR interaction techniques for co-located settings.

2 RELATED WORK

2.1 Collaboration in Augmented Reality

Collaboration has been a long-term topic in the area of Augmented Reality [3, 8, 9, 27, 40]. Collaborative AR systems have been classified within the classical Computer-Supported Cooperative Work (CSCW) time-space matrix, as well as additional categories [9, 42]. For example, Guo et al. explore the collaboration of users across time (synchronous/asynchronous) and space (co-located/remote) with their open-ended AR application, Blocks [17]. They found that users enjoyed co-located, synchronous collaboration the most. Poretski et al. compare a building task performed with physical objects and AR objects, respectively, to examine how co-located collaborative mobile AR affects users’ coordination. They find differences in users’ task allocations, formations, number of movements, and deictic gestures in the two conditions. They report that users move more and use more different formations, but they use less deictic gestures and are more likely to allocate tasks in different areas [39].

However, more research is still needed on co-located collaboration in AR. Malinverni et al. compare two paradigms of AR interaction, “Window-on-the-World” and “World-as-Support,” to examine primary school children’s understanding of space and how collaboration emerged among them when playing an AR mystery game. They present a conceptual framework to distinguish the strengths, weaknesses, and potentials of mobile and projection AR [31]. Wells and Houben investigate collaboration with a mobile AR application that allows multiple users to collaborate simultaneously. Their study examines how users work together around a tabletop, performing different tasks, and categorizes the way in which they collaborate into six different categories. The paper highlights context switches, collaboration styles, and device handling as three areas of challenge in collaborative mobile AR applications [50]. Dagan et al. explore playful co-located interactions with mobile AR in Project IRL. In their study, groups of participants interacted with
five different AR applications and found that device arrangement shapes user social engagement, which can be actively used in designing playful applications [6].

Although there is a wide agreement that AR has some particular properties with its spatial and situated nature, which can potentially leverage co-located collaboration [3, 6, 50], the AR field is only beginning to explore this landscape. There is still a lack of shared terminology in this area, and more work is needed to examine how the design of co-located AR applications shapes collaboration between users.

2.2 Spatial Collaboration

The increasing embedding of computing in our physical environments (e.g. interactive tabletops and mobile spatially aware computing) has spurred an interest in concepts and frameworks that allow for articulating spatial collaboration and social interaction while considering the complex interplay between the environment, technologies, and co-located people [13, 14, 29, 35, 45]. For example, proxemics is increasingly influential in the field of HCI research [2, 13, 29, 35], as we elaborate in the following section. Proxemics is often complemented by the F-formation system [28] which describes a variety of spatial patterns in group formations; for example, a common pattern is that groups are organized in a semicircular shape to be able to maintain eye contact while engaging with a shared object in the space between them [34]. F-formations have become a well-established framework and notation in the field of HCI for analyzing spatial patterns and possible transformations of these by designing interactive technologies [15, 34].

Studies of tabletop collaboration have also contributed notions of collaboration styles [25, 44], depicting collaboration styles ranging between loose collaboration and close collaboration, for example, working on different problems or sharing of the same view [25]. This work has informed recent research on collaborative styles in collocated AR [50], for example, Distributed View with Discussion and Single Shared View through one device. What is troubling about bringing these collaboration styles to the field of HCAR is that they depict different levels of collaboration while tying them to very particular F-formations. Across studies of different spatial technology platforms (AR [50], tabletops [25, 44], mobile games [45]) there is a shared conception of a hierarchical level of collaborative activities, and there is also a shared understanding that we need to consider dynamics and transitions in collaboration styles [15, 44, 45], and offer flexibility in collaboration styles [14, 44]. Finally, it has been suggested that developing a better representation of formations and their dynamics beyond what F-formations can provide can serve as a vehicle for developing better collaboration models [45].

2.3 Proxemics

The challenges outlined above bring us to the area of Proxemics. Proxemics is a research area that is growing out of anthropology [18], which articulates how people use space, in culturally dependent ways, to enact their intention of engaging with co-located others. Proxemics has also been influential in the field of architecture (e.g. [11]).

With the notion of Proxemic Interaction [13], the tenet is that insights from proxemics can serve to levitate ubicomp visions. Proxemics can provide ubicomp designers with increased sensitivity towards spatial implications and opportunities for mediating interactions with technology. The concept draws attention to how people orient and distance themselves from devices and to how dimensions such as distance and orientation can serve as ubicomp sensing possibilities for designing interactions with digital devices [2, 13].

In addition, it has been pointed out how interactive systems in general configure interpersonal spatial configurations in terms of Interaction Proxemics [14, 35]. More broadly, proxemics have been proposed to serve to increase socio-spatial literacy [29] in HCI around the implications of interactive
systems for collaboration. Based on studies on the use of imaging technologies in a surgical setting, Mentis et al. coin the terms perception, deixis and control proxemics. These dimensions are used to articulate how the spatial layout and interaction capabilities of interactive technologies condition the way people can position and orient themselves to be able to perceive digital content, make deictic references the content, and finally control the digital content. As an example, when surgeons collaborate in an operation theater and one surgeon wishes to make a deictic reference to a point of attention on an x-ray image for her colleagues to be aware of, she can either use a mouse (which is not very suitable for a disinfected surgeon), or she can point with her hand. But in this setting, the size and orientation of the screen and her distance from the screen restrict her opportunities for referencing a single item so that her colleagues can see [35].

Proxemics have also been discussed in the domain of play [16, 37], where it has been illustrated how the deployment and attention to spatial characteristics of sensing capabilities to detect interpersonal distances can serve to engage players in novel types of play activities mediated by digital technology [37]. More generally, the domain of play has often served as a fruitful arena for the exploration of "sociotechnical innovation" [24] in part formed by notions of proxemics; for example, "We found ourselves returning again and again to conscious shaping of the relationships between and among players spatially" or exploring spatial mechanics such as holding hands [24, 36] or novel roles for the mobile device, for example as a wearable [23] or as a low-resolution display [36].

While proxemics is increasingly gaining traction in the field of HCI, ubicomp, and play, it has yet to be used to inform the design of AR systems and to articulate the socio-spatial qualities and dynamics of such systems.

2.4 Proxemics for AR

Research on the operationalization of proxemics for the design of AR systems is sparse. Despite having gained traction in VR research, there are only a few works that draw upon the theory for AR, in particular. The main use cases here are to draw on proxemic relations in designing interactions with virtual agents [20, 38] or designing toolkits to design AR applications [32, 51]. Most related to our concerns, it has gained traction in interaction design research for immersive collaborative analytics [12, 21], where interactions demonstrate how proximity between users can inform how to facilitate collaborative interaction with immersive visualizations.

3 A PROXEMICS LENS FOR CO-LOCATED COLLABORATIVE AUGMENTED REALITY

We aim to develop a socio-spatial literacy to understand how the design of AR systems affects co-located collaboration. To achieve this goal, we synthesize concepts from proxemics theory to create a vocabulary that describes the socio-spatial dynamics in group collaboration among co-located users. This vocabulary allows us to systematically consider design rationales and alternatives of handheld collaborative AR (HCAR) systems based on how they shape the socio-spatial nature of co-located collaboration. In the following sections, we describe the individual dimensions and how they interplay with each other. Additionally, we demonstrate how this lens can be used analytically through the articulation of previously presented systems.

3.1 The Interplay between F-formations, Collaboration Styles, and Physical Features of Space

As virtual content in AR applications is situated in the physical world, we argue that AR interfaces should be understood as working in interplay with the spatial configuration of people, devices, and the physical space to shape people’s opportunities for collaborating with co-located others.

In this section, we show how to operationalize proxemics for understanding collaborative mobile augmented reality (AR) by examining how it relates to existing mobile AR systems. Drawing on
examples from previous work, we highlight how collaborative mobile AR can take various forms, contributing to the establishment of a vocabulary for enhancing socio-spatial literacy in design trade-offs regarding mobile AR systems. To articulate the impact of different systems on group dynamics, we use the F-Formation system [28] to visually illustrate spatial patterns. In conjunction with these illustrations, we use three dimensions of Interaction Proxemics [16, 35] – perceptual, deixis, and control proxemics – to explain how a group’s spatial arrangement in the physical environment facilitates different styles of collaboration and transitions between them. Specifically, we use these three proxemic dimensions to articulate the following concerns of co-located communication needs in AR systems:

- **Configuring perceptual proxemics**: The support for achieving shared or private perspectives on AR objects and spaces.
- **Configuring deixis proxemics**: The support for expressively communicating through deictic referencing in the shared AR space.
- **Configuring control proxemics**: The support for configuring the access to control and manipulation of AR objects.

Contextualizing these three proxemic dimensions for handheld collaborative AR (HCAR) systems, we can use prior handheld AR systems as examples of how the design of such systems can influence the social and spatial configurations of co-located collaborators. For instance, in ScholAR [41], two students work together on AR math exercises using a single mobile device. This type of collaboration requires users to be in close proximity to share AR content perception, fostering a closely coupled collaboration. However, control of the application is limited to the user holding the AR device. In HyperCubes [10], students collaborate around a single AR device and multiple tangible cubes. As with ScholAR, the students have a closely coupled collaboration and must be close to each other to share AR content perception. However, the tangible cubes allow all users to interact with the system without holding the device. As the virtual content is anchored to the physical cubes, the users can directly share deictic gestures towards the physical objects. In Blocks [17], co-located users build AR structures, with the AR content anchored to the floor. The users each have their own device with a networked connection synchronizing their virtual content. When oriented towards virtual content, they both perceive and control the virtual content. In Meta-AR-App [48], co-located students sit at their own tables, each with their own device and tangible setup, collaborating by uploading, sharing, and downloading AR content. In this case, each student has control of their own setup, and sharing perception and deictic gestures happen through the system. The collaboration styles shift between loosely coupled, where each user works on their own tasks, and more tightly coupled, helping each other by sharing perception and deictic gestures. Articulating these examples from the perspective of perception, deixis, and control proxemics illustrates how F-formations and collaboration styles can be related in different ways and how the physical features of space (cubes, floor, and tables) also serve to configure possibilities for orientation and collaboration.

### 3.2 Cross-Device AR for Aligning with Reality and Going Beyond

Beyond understanding proxemic relations of co-located collaborative AR systems, we seek to develop a design lens for considering how cross-device interaction techniques [4] for multi-user handheld AR can enable new forms of proxemic relations for collaboration. For instance, when comparing the spatial cross-device configurations enabled by Meta-AR-App, ScholAR, and Blocks, we observe that ScholAR and Blocks enable a natural form of F-formation around shared virtual content as if the users organized around a real object. On the contrary, the co-located networking of devices for cross-device communication in Meta-AR-App shows how AR systems can also expand
the possibilities of using space for collaboration. These systems offer examples at each end of the Reality & Beyond continuum that we propose (see Figure 3).

As demonstrated in the concept of Proxemic Interaction [2, 13, 33]; spatial interaction can be designed to align with how people move in space, for example, to trigger implicit responses on a display UI as people move closer to the physical display. In particular, Marquardt et al. extend how users engage in F-formations and use micro-mobility gestures to share across devices [33]. Several studies on co-located collaborative AR show how these dynamics inherently emerge as co-located users arrange in F-formations for co-located collaboration around handheld AR (e.g., CollabAR [50], Project IRL [6], Blocks [17]). From a design perspective, research on collaborative immersive analytics has investigated how to align with proxemics in physical reality for designing collaborative interactions with 3D visualizations [12, 21].

Even though augmented reality is anchored in the physical environment, the technology can still use the available cross-device possibilities to go beyond physical reality and overcome the constraints of the physical socio-spatial relations through wireless co-located sharing of views and controls. Grønbæk et al. have explored how this perspective can support interpersonal flexibility in cross-device systems [14].

For the remainder of the paper, we will focus on how a proxemic lens may generate new ideas for designing interaction techniques with handheld AR to support co-located collaboration. In particular, we will use proxemics as a lens to understand how AR interactions can align with vs. go beyond physical reality. In other words, we systematically explore the following two sides of the coin: First, we consider how AR interactions can naturally extend the socio-spatial relations as they play out with perception, deixis, and control in the physical space between users. Second, we consider how AR interactions can be used to overcome the constraints of physical socio-spatial relations by allowing for wireless cross-device sharing of perception, deixis, and control.

4 RESEARCH THROUGH DESIGN: PROTOTYPING AR INTERACTION TECHNIQUES

To guide our exploration of a wider design space for co-located AR, we draw inspiration and motivation from proxemics and CSCW literature and operationalize particular theoretical notions from prior work; collaboration styles [39, 44, 50] and the dimensions of interaction proxemic—perceptual, control, and deixis proxemics [16, 35]. We apply these notions together as a lens to co-located collaborative handheld AR—a type of system to which they have not previously been applied. This leads to the construction of a design space, including exemplar interaction techniques which are articulated in terms of their proxemic consequences.

We contribute a terminology for articulating design intentions around collaboration with HCAR systems, which can serve to inform future explorations of this emerging design space. This is early work exploring a theoretically grounded design exploration, and therefore we also provide initial evaluations of this work in terms of demonstrations rather than usage [30]. In terms of demonstration, we provide both an exploration of a design space and, in addition, two scenarios of envisioned usage [30]. This research does not validate that the proposed interaction techniques and enriched design space will be used in line with the proposed scenarios. This will require substantial further research in terms of prototypes and usability work. Further, in order to limit the scope of the design space explorations, in this paper we focus on AR systems that are based on mobile technologies. Future research is needed in order to broaden these investigations to encompass other relevant technological platforms for collaborative AR systems, such as projection-based systems or head-mounted displays.
4.1 Multi-user AR prototype

To support these design explorations, we build a multi-user mobile AR application, where different interaction techniques could be explored to support co-located collaboration. The prototype allows multiple users to create different AR models such as houses based on small blocks and collaborate around the created content. The prototype supports users in sharing a fully synchronized AR experience as illustrated in Figure 2. The interface supports users in creating block models, saving and reloading models, and testing different interaction techniques. This open-ended prototype made it possible to explore and develop different interactions from out-of-the-box techniques that align with reality to other techniques that support flexible interpersonal positions and orientations.

The prototype is an iOS application running on up to 5 devices. It is built in Unity and is based on Unity’s AR framework AR Foundations [46]. For creating the multi-user functionality, we used AR foundations’ collaborative participants and Apple’s Multipeer Connectivity [1].

5 REALITY & BEYOND: DESIGNING COLLABORATIVE AR INTERACTION TECHNIQUES

To explore proxemics as a lens to generate new ideas for supporting co-located collaboration in mobile AR systems, we systematically explore how to design interaction techniques to align with reality (i.e., follow the patterns of physical interpersonal space) and go beyond reality (i.e., break with those same patterns). In doing so, we focus on three dimensions of collaborative actions in terms of proxemics — perception, deixis, and control. As the outcome of our design space exploration, we map out the interaction techniques on a continuum, ranging from techniques that align with reality to techniques that go beyond the constraints of physical socio-spatial relations. The continuum and design space exploration can be seen in Figure 3.

On the left side of the continuum, we have techniques that align with reality in that users’ interaction with AR content is constrained by interpersonal distance and orientation, by the devices, the physical layout of the space, and the position of the AR content. These techniques are often found in out-of-the-box multi-user AR systems, where virtual content acts as much as possible as real objects and is fully shared between the users. At the other end of the continuum,
Fig. 3. The design space of collaborative AR interaction techniques. The 10 interaction techniques explored ranges from aligning with reality to beyond reality.

we have the techniques exploring how the users can collaborate while being fully flexible in their interpersonal distance and orientation, i.e., the techniques that go beyond reality and use the possibilities of networking between the devices. We have techniques that mix the two approaches between the two ends. Close to alignment with reality, we can design techniques inspired by proxemics interaction [2, 13] that extend the enacted proxemics. Further towards going beyond reality, we have techniques that add flexibility in interpersonal distance and orientation but draw upon reality. In the following, we present each interaction technique explored to support perception, deixis, and control and illustrate how they align with or go beyond reality.

5.1 Configuring perception proxemics

5.1.1 Basic AR Perception. In augmented reality applications, virtual content is anchored to the physical world; thus, the users’ perceptions are defined by their distance and orientation to the content. To share their perception of virtual content in most basic AR applications, users need to see the content from the same distance and angle by physically standing closely, either looking through a single device or through each of their own devices. The size of the mobile device and the field of view constrain users to stand in a specific f-formation to share perception.

5.1.2 Freeze Frame. By utilizing the possibilities of mobile devices, we can overcome the constrained interpersonal distance and orientation when sharing perception. In Freeze Frame, known from remote collaboration [5], users can take a snapshot of virtual content from the perspective they
wish to share (see Figure 4). This allows them to attach the content directly to the device instead of having to perceive the content through the device. When using this technique in co-located collaboration, it enables the user to make micro-mobility gestures with the device enabling more flexibility in their interpersonal distance and orientation.

Fig. 4. In Freeze Frame Alice freezes a perspective on the AR content (A1). Alice can now use micro-mobility to share perception of the AR object with Beth with flexibility in interpersonal distance and orientation (A2).

5.1.3 Remote Peeking. While Freeze Frame allows for more flexibility in user interpersonal distance and orientation, users are still required to be relatively close to each other to perceive the attached content on the mobile device. In Remote Peeking (Figure 5), the networking possibilities of the devices allow users to peek at other users’ perspectives. For example, if Alice wants to peek at Beth’s perspective (see Figure 5(A1)), Beth starts by selecting the location of Alice’s device (Figure 5(B1)). This enables the peeking view, allowing Beth to perceive the content from Alice’s perspective (Figure 5(B2)). Beth can switch between the peeking view and her own view (Figure 5(B3)). Beth does not need to physically move to see Alice’s perspective of the virtual content. This technique allows users to be flexible in their interpersonal distance and orientation. Still, it draws upon reality to understand which perspective they are seeing, meaning that the peeking user needs to be able to see the user they want to peek on.

Fig. 5. In Remote Peeking Beth can peek on Alice’s perspective (A1) by selecting the position of Alice’s device (B1). Beth can now swap between seeing Alice’s perspective (B2) and her own perspective (B3) in focus.

5.1.4 Perspective Broadcasting. The Perspective Broadcasting technique is similar to Remote Peeking, but in this technique, the initiative comes from the user sharing perspective instead of the peeking user. Users can broadcast their current perspective to all other users no matter where they are physically located in the space. This allows users to be fully flexible in their interpersonal distance and orientation while still being able to share their perception of the virtual content.
5.2 Configuring deixis proxemics

5.2.1 Basic AR Deixis. Even though AR content imitates physical objects in the way they are anchored in physical space, Poretski et al. [39] found that users use fewer deictic references when collaborating around virtual content in AR compared to physical objects. In basic AR, using deictic references to the AR content often means pointing to the content as if it were real. Either directly towards the objects or on the screen. In mobile AR, the devices have a limited field of view, making it challenging to see both the virtual content and the deictic references. Thus, sharing deictic references is constrained by the users’ interpersonal position and orientation.

5.2.2 Spatial Reference. With Spatial Reference, a user can anchor a spatial reference in space to make deictic references later, as seen in Figure 6. Alice creates a spatial reference on a perspective she wishes to save for later (Figure 6 (A1)). She sees the reference as an AR object pointing (Figure 6(A2)). Beth sees the spatial reference on her device (Figure 6 (B1)), and when Alice points roughly in the direction, Beth easily follows her deictic reference (Figure 6 (B2)). This technique draws upon reality by augmenting a position in space, but it enables users to share more precise deictic references in more flexible f-formations.

5.2.3 Remote Sketch. Where Spatial Reference creates more interpersonal flexibility, users still need to be oriented towards the virtual object and reference point to understand the deictic references. With Remote Sketch (Figure 7), the users can be even more flexible in their interpersonal position and orientation while sharing deictic references. Remote Sketch builds on Freeze Frame by allowing users to broadcast the frozen frame to other users and annotate the frame to all other users as seen in Figure 7. Alice freezes a frame and broadcasts it to the other users no matter where they are (Figure 7 (A1)). She sketches on the frame to reference some specific detail (Figure 7 (A2)). Beth receives the frame and sees Alice’s live sketch on top (Figure 7 (B1)). By freezing the frame, the user making the deictic reference is flexible in moving to a more comfortable position before making the references. Other users can see the deictic references from anywhere, enabling flexible f-formations.

5.3 Configuring control proxemics

5.3.1 Basic AR Control. As the input device for virtual objects in mobile AR is in the hands of users, in basic AR applications, users can technically control objects when they are within the field of view of their device. But in practice, the control is constrained by users’ personal space, fixed and semi-fixed features of the environment, and social norms. For example, you would rarely
Remote Sketch

Alice can freeze a frame and share it with everybody (A1). She sketches the frame in order to explain a detail (A2). Beth sees the frame and follows Alice’s sketch in real-time.

5.3.2 Proximity Threshold. While basic AR control follows physical and social rules, these can also be enhanced in the system. With Proximity Threshold, users can only control objects within close proximity (Figure 8). Beth is manipulating the AR in front of her (Figure 8 (B1)). Alice sees that the object is there, but she cannot see any details of the object (Figure 8 (A1)). When approaching the object, Alice now sees the object and can start manipulating it along with Beth (Figure 8 (A2)). Since Alice has to be close to the object to see and manipulate it, she also moves closer to Beth, who is already interacting with the object. Beth can easily see if other users have control of the object along with her. In this way, the AR system extends the enacted proxemics.

Privacy Fence

With Proximity Threshold, users have more privacy around virtual objects within their personal space, but the control of the virtual environment still has socio-spatial meaning. With Privacy Fence, users can create their own private territory anywhere. The user defines a spatial fence, where everything they put inside the fence will be their private objects completely hidden from other users, giving them full control as seen in Figure 9. If Alice wants to work on something private along with the public content, she creates a Privacy Fence next to the public object (Figure 9 (A1)), adds the content she wants to work on inside (Figure 9 (A2)), and starts manipulating her private content (Figure 9 (A3)). Beth still only sees the shared content (Figure 9 (B1)).
(B1)). This technique allows users to be completely flexible with what they want to share with others and what they want to keep private by moving objects in and out of the fence.

Fig. 9. In Privacy Fence users can create their own private territory anywhere. Alice creates a Privacy Fence next to a shared object (A1-A2). Alice works on her private object (A3), while Beth still only sees the shared object (B1).

6 EXAMPLE SCENARIOS

To demonstrate how the conceptual lens can be used as a tool for developing new AR applications, we consider two different domains, which have already been explored within co-located AR [8]. This includes an AR application for architectural design and an AR application for education. With these examples, we want to illustrate how we can use the proxemics lens to design for flexible social interaction. The scenarios illustrate how the interaction techniques can be complementary and support the dynamics of the collaboration over time. In addition, they illustrate the potential value of interaction techniques that goes beyond reality.

6.1 Architectural Design Meetings

An architect company wants an AR application where their architects can collaborate around 3D models of building designs in internal design meetings and external client meetings. In internal design meetings, architects meet in a meeting room to discuss different specific designs and agree on the details of the designs. Most of the time architects should have a tightly coupled collaboration discussing the design of a building (see Figure 10). To rapidly shift between overview and details, sharing perception should have a low proxemic threshold. If the architects are sitting side by side, sharing perception is easy by either looking at each their own device from nearly the same angle, but if one is sitting at the opposite side of the table the proxemic threshold is much higher. In this case, providing multiple alternatives, such as also enabling Perspective Peeking, could create a low proxemic threshold for all users and support these rapid shifts, as illustrated in Figure 10.

When the architects find problems with the design they need to be able to make detailed deictic references to the problem areas and remember them for later. Here, Spatial References can be valuable to support both referencing the problems when they are found and the spatiality of the reference point makes it easy to remember and revisit the point.

Architects have symmetric roles in the internal design meeting, whereas, in the external client meeting, the roles between architects and clients are asymmetric, creating other needs for collaboration. At the client meeting, architects and clients discuss the design prepared by the architects (see Figure 11A). The architects want to show a detailed design to the clients. Using the Perspective Broadcast technique, the architects’ perspective is shared with everyone without changing the current f-formation, as illustrated in Figure 11B. In the meeting, the client might not like some of
Fig. 10. A closely coupled collaboration between architects in an internal design meeting. A) The architects view and discuss the overall design of the building. B) They shift into discussing a detail, one peeking over the shoulder (Basic AR Perception), while the others use Remote Peeking to see the detail. C) One creates a Spatial Reference highlighting the detail. D) Later, one of the architects points towards the Spatial Reference to reference the detail again.

Fig. 11. A meeting between architects (green) and clients (yellow). A) The architects and clients discuss the overall design of a building. B) One of the architects shows details to everyone using Perspective Broadcasting. One of the architects breaks out of the closely coupled collaboration and creates a Privacy Fence to work on a new design without interrupting the others’ conversation.

the designs. In this case, an architect would like to create a design variation. By creating a Privacy Fence next to the shared model, it is now possible to privately create a variation of the design without breaking out of the f-formation and interrupting the discussion taking place, as illustrated in Figure 11C.

6.2 Classroom Group Work
In a classroom setting, group work is a common activity in which students work together on an exercise while the teacher moves around to assist the groups. Designing an augmented reality (AR) application for this context requires considering the collaborative work among students and the teacher’s role in the collaboration. In group work scenarios, students have similar roles and ideally adopt a closely coupled collaboration style. From the teacher’s perspective, the teacher moves around the classroom to discuss the exercise with each group and is only interested in helping one group at a time.
Using a Proximity Threshold ensures that the AR content is only perceived and controlled once close to the teacher. For example, when the teacher approaches a group to help them, the content appears once within close proximity, as illustrated in Figure 12A-B. Additionally, the Freeze Frame feature allows the teacher to show details to one student by attaching the view to the device and turning the device away from the AR to display the information, as seen in Figure 12C. If the problem is relevant to all students, the teacher can keep the frame on the device, move away from that group and use Remote Sketch to talk to the whole class, and broadcast a live sketch to everyone, as shown in Figure 12D. These features enable teachers to better manage group work in a classroom setting using AR technology.

7 DISCUSSION
In this section, we summarize the key insights from this exploration of proxemics as a lens for co-located collaborative AR.

7.1 AR for Aligning with and Going Beyond Reality
In this work, we have explored the potential of designing AR applications that not only align with reality, but also leverage the networking capabilities of mobile AR devices to go beyond reality. Our focus was not to compare different systems or judge them as better or worse, but rather to showcase the possibilities of designing collaborative AR systems. Our exploration of the design space for interaction techniques based on the dimensions of Interaction proxemics [35] – perception, deixis, and control – highlighted how interaction techniques can be based on reality while also going beyond it [19]. This indicates how we can utilize the medium to transcend our physical and bodily...
limitations. Our contribution is not only to demonstrate individual interaction techniques, which
have been explored before in the context of AR, but also to present a broader design space for
interaction techniques that can be used in co-located collaborative AR.

7.2 A Many-to-Many Relationship between Collaboration Styles and F-Formations

Our model of group dynamics builds on prior research on of collaborative coupling styles [39, 44, 50],
which are based on empirical studies. We presented interaction techniques derived from the
proxemics lens that expand the possible forms of collaboration styles from a different perspective.
This presents a novel potential for AR to transform the one-to-one relationships between coupling
style and interpersonal distance [44] as well as between coupling style and device configurations [50]
that have been identified in empirical studies. Using the proxemic lens, we show that group dynamics
can be understood as a many-to-many relationship between F-formations and collaboration styles.
Collaborative AR systems can enable users to engage in the same collaboration style while enacting it
in various F-formations. Conversely, such systems can also allow users to switch between multiple
collaboration styles while maintaining the same F-formation. For instance, both PERSPECTIVE
BROADCAST and REMOTE SKETCH enable users to be in and transition between different F-formations
while still keeping the same collaboration style, such as discussing the same detail of the virtual
content. The PRIVACY FENCE in the client meeting is an interaction technique that enables users to
transition between collaboration styles while keeping the same F-formation, such as an architect
shifting from closely coupled collaboration with the clients to working on something private for a
brief period before returning to the shared discussion.

7.3 Extending vs. Reconfiguring Proxemic Relations

Designing for going beyond reality enhances flexibility in socio-spatial configurations, but also adds
complexity to the application in terms of user understanding. Remote-control interactions, which
provide flexible options, are less natural because they do not immediately extend our physical
spatial relations, which we rely on in our interpretations of non-verbal cues. Therefore, future
investigations should focus on designing appropriate awareness cues to address questions such as
how users understand the application’s functionalities, how different ways can be used to share
perception and deictic gestures, and who controls the content. For example, with the REMOTE
PEEKING technique, users can now peek into other users’ perspectives flexibly, but how do they
understand who is seeing what? In PRIVACY FENCE, a user can work on something private right
in front of you that you cannot see. Although awareness cues have been extensively explored
in remote collaboration [49], more work is needed to understand how these cues can be used to
support co-located collaboration. This also highlights the tradeoff between adding flexibility and
understanding the application.

7.4 Limitations and Future Work

Based on our design exploration, we have mapped out different interaction techniques on a contin-
uum going from aligning with reality to going beyond. However, using a design space exploration
and evaluation by demonstration [30] has certain limitations. As the interaction techniques are
based on an exploration and not an extensive review, the presented techniques should not be seen as
an exhaustive list, but rather as a starting point for exploring the design space further. Furthermore,
the interaction techniques have not been evaluated in usage, so more work is needed in order to
further validate the techniques and in addition study their interplay and how they are useful in
specific contexts and domains.

In this work, we have focused on AR systems based on mobile technologies. In mobile AR, the
device acts as a portal to perceive the AR content anchored in the physical space. The limited
field of view (FoV) of the mobile device creates some challenges in the collaborative setting, but the mobility of the device also creates opportunities as shown in the design exploration. In other AR technologies, AR devices are in the same way a portal to the AR world, but devices have different roles in the physical environment. E.g. AR glasses are attached to the user’s head and in spatial augmented reality the virtual content is attached directly on top of the physical space. This connection of the viewing device to either the user or the environment somehow simplifies the relations between users, devices, space, and AR content compared to mobile AR, but we believe that proxemics still has a lot to offer in understanding and designing for these display types. Future research is needed in order to broaden the space for using proxemics to design for collaborative AR.

8 CONCLUSION
In this work, we have demonstrated how proxemics theory can be used as a conceptual lens articulating collaborative AR systems and their properties. Through a design space exploration, we explored how interaction techniques for handheld multi-user AR applications can be designed to either align with or go beyond reality. This work has highlighted how there can be a many-to-many relationship between different collaboration styles and f-formations. Based on this exploration, we present reality and beyond as a continuum for designing co-located collaborative AR systems, illustrating how we can design AR systems to extend enacted proxemics or support flexibility in interpersonal distance and orientation. Finally, we highlight how proxemics can be used to understand the tradeoffs in the design of AR with relation to perceptual, deixis, and control proxemics.

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REFERENCES


