A Survey of Needs and Features for Augmented Reality Collaborations in Collocated Spaces

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In this paper we contribute a literature review and organization framework for classifying the collaboration needs and features that should be considered when designing headset-based augmented reality (AR) experiences for collocated settings. In recent years augmented reality technology has been experiencing significant growth through the emergence of headsets that allow gestural interaction, and AR designers are increasingly interested in using this technology to enhance collaborative activities in a variety of physical environments. However, collaborative AR applications need to contain features that enhance collaboration and satisfy needs that are present during the group activities. When AR designers lack an understanding of what collaborators need during an interaction, or what features have already been designed to solve those needs, then AR creators will spend time redesigning features that have already been created, or worse, create applications that do not contain necessary features. While much work has been done on designing virtual reality (VR) collaborative environments, AR environments are a relatively newer design space, and designers are lacking a comprehensive framework for describing needs that arise during collaborative activities and the features that could be designed into AR applications to satisfy those needs. In this paper we contribute a literature review of 92 papers in the areas of augmented reality and virtual reality, and we contribute a list of design features and needs that are helpful to consider when designing for headset-based collaborative AR experiences.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)** → Interaction paradigms → Mixed / augmented reality; • **Applied computing** → **Education** → Collaborative learning

KEYWORDS: Augmented Reality, Virtual Reality, Collaborative Virtual Environments, Collaboration Taxonomies

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1 INTRODUCTION

Augmented reality (AR) technology has been expanding in popularity in recent years due to the pervasiveness and increased power of mobile devices, as well as increased availability of optical see-through headsets such as the Microsoft Hololens [99] and Magic Leap [100]. Head-mounted AR devices contain sensors for detecting a user's movements through a physical workspace, and newer devices can sense the positions and gestures of a user's hands, as well as the shape of physical objects [99]. This enables virtual content to be overlaid on physical objects while users perform manipulations with their free hands. This is in contrast with traditional AR experiences where users interact through screen-based interactions on hand-held smartphones or tablets. Headset-based AR experiences are increasingly being designed for contexts where multiple users must collaborate to perform coordinated tasks around physical objects, such as in the context of medical operating rooms where users need to see visualizations of patients' anatomy while operating [43], industrial maintenance where workers interact with instructions overlaid on physical machinery [3], and educational maker spaces where students see electricity and magnetic phenomena while manipulating objects [68]. It is expected that as sensor hardware continues to evolve, AR headset applications will increasingly be designed and used for such contexts. The design space of collocated collaboration with AR headsets provides opportunities and challenges. Enhancing collaborations through augmented reality can allow collaborators to do things they may not be able to do otherwise - such as brainstorming by drawing 3D shapes on physical objects, annotating objects with audio recordings of previous conversations, or visualizing and editing 3D structures relevant to the physical environment [22]; but at the same time, AR technology presents challenges to collaboration, because participants may not be able to see each other due to AR headsets covering their faces, or may not be able to see what their peers are working on because virtual objects may occlude the view [67].

As AR designers create experiences for collocated collaboration contexts for hands-free headset-based interactions, it is critical to understand the variety of needs that team members have in such spaces, as well as the features that can be designed in AR environments to meet those needs. Designing experiences for supporting collaboration is a challenging task because AR applications should be designed to support specific collaborator needs such as maintaining awareness of others, directing peer attention, synchronizing tasks, etc. At the same time, there may be multiple features that can solve those needs, such as maintaining awareness by visualizing a peer's gaze direction, or visualizing their whole field of view, or visualizing a coloured heatmap of where their attention has been recently. Without understanding what features and needs have been considered in previous literature, AR designers may not know what needs to consider and thus not design those into new systems, or designers may be aware of a need but not know which features can be implemented to solve that need. In this paper we aim to address this issue by performing a literature review.

The current research literature is lacking a systematic understanding of what features and needs have been considered for supporting collaboration in collocated AR experiences. We address this by performing a systematic literature review, to identify the features and associated needs that have been previously considered. Our research question is: *What needs and features should be considered for supporting collaboration in headset-based collocated AR experiences?* In the rest of this paper, we first review related literature on collaboration and virtual environments. We then discuss the methodology and data sources for our literature review, followed by results. We conclude with broader discussion and limitations.

2 RELATED WORK

In the area of computer supported cooperative work, there has been much work in the generation of taxonomies and frameworks that identify dimensions of organizing characteristics of collaboration, and classify technologies that support such characteristics. High level classifications can be used to categorize collaborations in dimensions such as space (e.g. participants being collocated vs. remote) [34], time (e.g. real-time vs. asynchronous communication) [34], predictability (e.g. directed video conferencing vs. broadcast emails) [11], communication types (e.g. presentation vs. conversation vs. collaboration) [57]. In our research we are interested to understand collaboration characteristics in the context of collocated synchronous interactions, and how to support those interactions. To understand the needs of collaborators in such contexts, it is important to investigate lower-level categorization schemes which describe more specific behaviours.

Previous research has highlighted specific behaviours that contribute to successful collaborations. Robertson [71] discussed the role of embodiment and actions of the body in collaboration. For instance, collaboration is enhanced when team members are aware of others' bodies, when they can use their own bodies to indicate focus of actions, or use bodies to manipulate shared items. This research also identifies how a group coordinates through activities such as participants guiding the focus of group attention, by splitting and merging the team into subgroups, or by contributing at appropriate times during group conversations. Gutwin and Greenberg [28] investigated the role of awareness as a critical component of successful collaborations in small groups. Collaborations benefit when group members can be aware of others, in the present or in the past, for instance by being aware of "who" is in the space, "what" they are working on, and "where" they are located or attending to. Designers should design for such awareness behaviours when designing new systems. Awareness enables more complex activities such as coordination [20]. Coordination is the process for synchronizing actions across different team members, enabling harmonious group actions [77]. Coordination happens at different time scales and can describe longer-term activities such as ensuring group members synchronize work after performing separate tasks on co-authored artifacts, or shorter-term activities such as coordinating attention and movements when carrying physical objects together [16,73]. Although it is known that these kinds of behaviours are important for collaborations, and they contribute to the overall form and success of collaborations [57], research is lacking about what features exist to support these behaviours for collocated augmented reality environments.

Augmented reality and virtual reality are similar technologies as they allow users to use their whole body to interact with computer-generated virtual objects. AR experiences overlap computer-generated content on real world spaces and objects, while VR experiences fully replace the real world with computer-generated content. In such environments, users can interact with virtual content in single-user experiences, or together with others in collaborative virtual environments (CVEs) that permit multiple users to interact with each other and with shared virtual objects [25]. Frameworks and taxonomies have been created to conceptualize the characteristics of virtual environments. Milgram et. al. [50] classifies different types of experiences on the Mixed Reality (MR) spectrum, where fully real environments are on one side, fully virtual VR environments are on the other, and augmented reality environments in between. Because of this relationship between AR and VR environments, some researchers use the term mixed reality to denote experiences where AR and VR users collaborate.

Because of the technological similarities between AR and VR environments, specifically that users can see and control computer-generated 3D objects (either as overlaid on the real world in AR, or fully immersed in a digital world in VR), there is possibility of transferring collaboration features between these types of environments. Many features that are designed for VR collaborations (which are typically not collocated, due to the fully immersive nature of the technology), or for non-collocated AR collaborations, may be transferrable to collocated AR environments. For example, VR applications typically involve pointing features such as laser pointer beams radiating from a user's virtual hand as they point at objects [47], and this feature can now be transferred to collocated AR environments where a head-mounted devices can monitor the user's hands [55]. However, not all features are transferrable – for instance, VR designers have created features to allow users to teleport to different parts of an environment or change their scale [81], or that prevent users from hitting real-world objects (such as chairs in their room) while they move in the virtual space [87]; such features may not be necessary or feasible in AR since users can see the real world. However, in AR there are other features such as the need to detect the shapes of physical objects [14] or the electricity passing through real circuits on the user's desk [88], which are not applicable to VR. Because of these overlaps, our review includes collaboration features that have been discussed in various AR and VR environments, but we focus on features that are specifically applicable to headset-based interactions in collocated AR settings.

As the field of virtual reality has existed for decades, multiple taxonomies have been designed for specifically classifying different types of features possible in VR environments, such as descriptions of how single users can annotate objects in virtual spaces [94], view and manipulate 3D menus [17], navigate [12], anchor objects [51]. For group activities in collaborative virtual environments, research has studied the types of features that are needed to enable collaboration. [16] argue that 3D virtual environments require special collaboration taxonomies because of the high emphasis on collaborators embodiment and spatial immersion which are not captured in traditional CSCW taxonomies, and which need to be addressed when designers create features for immersive environments. The authors highlight the need for design for aspects such as mutual awareness (e.g. of peers through embodiment as virtual avatars, of spaces and objects as virtually represented models), communication (e.g. through gestures, video and audio sharing), mutual interaction and sharing (e.g. permitting mutual engagement with objects and space). However, the research focuses in general on 3D virtual worlds, and does not describe the specific features that have been implemented to achieve these goals in VR or AR. In surveying the space of mixed reality experiences, [22] highlights the need for CVEs to support awareness and a sense of embodiment and communication, but the review does not focus on the features that achieve this. The review groups existing research into high level categories of time (synchronous vs. asynchronous), space (collocated vs. remote), symmetry of user roles and capabilities (symmetric vs. asymmetric), artificiality of environment (physical to digital). The focus on these broad characteristics allows to analyse groups of applications and trends over time, however the authors note that they focus mainly on mechanical aspects of the system or properties of the underlying technologies, and that a greater focus on the user experience would be better suited to capture details of the implementation scenarios researched. Our review addresses this need to capture implementation details, as we focus on the user experience design of features which enable the collaboration between participants, specifically applicable to AR collocated environments. [52] provides a survey of design considerations for VR environments, including design features for supporting awareness of what peers are looking at or working on, and features for supporting communication. Although not a systematic literature review of the literature and it is unclear how many papers were reviewed, the result is a list of features useful for consideration in designing VR collaborative environments. In contrast, in the present work we focus on features for collocated AR environments, and perform a systematic review collecting features as well as needs, while also identifying other aspects of collaboration such as coordination, instruction and creation.

3 MATERIALS AND METHODS

3.1 Data Sources

Articles for review were gathered via Google Scholar from conferences and journals that contain peer-reviewed academic publications on augmented reality and virtual reality, such as: International Symposium on Mixed and Augmented Reality (ISMAR), Virtual Reality Conference (IEEE VR), Virtual Reality Continuum and its Applications in Industry (VRCAI), Computer Human Interaction (SIGCHI), Transactions on Computer Human Interaction journal (TOCHI), Computer Supported Cooperative Work (CSCW), Computer Graphics and Interactive Techniques (SIGGRAPH), User Interface Software and Technology Symposium (UIST), Spatial User Interfaces (SUI), 3D User Interfaces (3DUI), Presence: Virtual and Augmented Reality (PRESENCE).

3.2 Inclusion/Exclusion Criteria

To be included in this review, papers had to meet all the following criteria: (1) discuss virtual or augmented reality (while containing the words "augmented reality" or "virtual reality" or "mixed reality"), (2) describe a system in which multiple users collaborate, (3) describe a system involving AR and/or VR headsets, (4) discuss a presently existing system (ex: no hypothetical or argument-style papers). Articles were excluded if they (1) described a system that was not using at least one headset (ex: we excluded systems where users only used mobile devices), (2) did not include a screenshot of a working system, (3) were papers that provide a survey or review of existing literature, and did not contribute a new system. When including papers, we included both AR and VR systems because features may be transferrable between the environments, as discussed in the previous section. However, we excluded features that are not applicable to headset-based collocated AR activities, for example VR features for teleportation or for detecting collisions with physical objects while moving in virtual worlds.

3.3 Methods

The papers were analyzed through a four-phase process. During *Phase 1 (Data Collection)*, papers were first gathered by all researchers from the different venues, ensuring they meet the inclusion and exclusion criteria. One researcher then checked that all papers meet the inclusion / exclusion criteria, and assigned papers for review to each researcher. In *Phase 2 (Extraction of Paper Details)*, a spreadsheet template was used by all researchers while reviewing papers, and used for extracting a list of features, needs and paper details used in this review. The categories included in the final coding were: types of tasks that were done by collaborators in each paper, locations of the collaborators (co-located or remote), measures used to analyze collaboration, technologies used in the papers (AR headsets, VR headsets, 2D devices, etc), objects that have been augmented if AR is involved, collaboration features observed in the paper, collaboration needs observed in the paper, and communication problems indicated in text. Researchers commonly coded 10% of papers while building consensus. If researchers disagreed during this initial consensus building portion, the disagreements were discussed as a group until agreement was were reached before proceeding with further coding. By the end of this portion, there were no disagreements between researchers when coding new papers. The remaining 90% of papers were coded independently by individual researchers. In *Phase 3 (Organization)*, while all papers were read and coded, all the individual features and needs were transferred into a collaborative mind map, and reorganized into clusters according to similarities. All researchers worked together as a group during this phase and in case of disagreements reached consensus through discussion. After 50% of papers were read, we identified clusters of high level features linked to high level needs, and then separated them into lower-level features and needs, while filtering features not applicable to headset-based collocated AR collaborations. While the remaining 50% of papers were read, the features found in the new papers were integrated into the mind map, and the categories were reorganized if new feature clusters appeared. The result of this phase is the categorization scheme presented in this review. Finally, in *Phase4 (Counting)*: each feature and need was associated with its original paper, in order to generate a linking between features and the types of technology and context each is suitable for.

Table 1. Resulting collaboration needs, and sample references that contain features addressing those needs.

Categories of collaborative needs	Example features
4.1 Collaborators need to be aware of others' attention and activities	
Collaborators need to stay socially aware of each other's presence, location and intention of action.	[2,39,42,45,46,63,74,85,92]
Collaborators need to see each other's emotions	[19,66,67]
Collaborators need to stay aware of the progress of synchronized tasks	[18,23,58,63]
Collaborators need to show/hide layers of the environment	[2,26,31,48,53]
Collaborators need to have information on demand	[7,29,32,40,48,63,89,97]
4.2 Collaborators need to be aware of the past	
Collaborators need to remember actions	[8,27,49,95]
Collaborators need to remember conversations	[4,15,27]
4.3 Collaborators need to coordinate attention	
Collaborators need to specify direction of attention	[5,41,45,53,64,76,84,85,92]
Collaborators need to specify objects of attention	[3,6,13,37,55,69,91]
Collaborators need to manipulate objects at the same time	[35,61,63]
4.4 Collaborators need to coordinate instructions	
Collaborators need to annotate objects	[9,30,41,76,82,85]
Collaborators need to guide others	[13,23,31,40,41,55,74,86,92]
4.5 Collaborators need privacy	
Collaborators need personalized information	[39,68,96]
Users need private space within a collaborative space	[27,38,44,75,82]
4.6 Collaborators need to manipulate virtual objects	
Collaborators need to move virtual objects	[6,8,13,21,30,59,70,78,79,82]
Collaborators need to modify virtual objects	[30,32,69,72]
4.7 Collaborators need to share the same environment	
Collaborators need to see the same virtual content	[74,83,92]
Collaborators need to have a smooth networked experience	[26,46,56,63,80]

4 RESULTS

Our review collected features from 92 papers, distributed among 18 categories of needs. The features and their associated needs are listed in Table 1 and described in the following sections. We report the results of the literature review by organizing results according to the collaboration needs that are being satisfied through each feature. The results range from more passive needs, such as collaborators needing to embody a shared environment, to more active needs such as methods for directing collaborator attention, to complex needs such as needing to create objects at the same time.

4.1 Collaborators need to be aware of others' attention and activities

Collaborators must have the ability to maintain awareness of the environment and of each other, in order to monitor tasks and synchronize collaboration.

4.1.1 Collaborators need to stay socially aware of each other's presence, location and intention of action. To help co-located AR collaborators stay aware of where others are facing and looking, [42] introduced a line segment drawn from users' eyes toward the viewing direction of the head, highlighting the collided objects. Eye gaze, captured through eye-tracking devices and shown through coloured rings, can also indicate the specific spot collaborators are looking at [74]. [45,63,74,85,92] suggested a "view frustum" feature (Figure 1 middle) like a coloured rectangular frame or head gaze boundary to show what area the other collaborator is able to see with their head position. Although such a feature is designed for remote collaboration, it is possible to apply it to collocated AR settings to view a peer's gaze. [46] designed the video in HMD see-through view to be as natural as possible while seeing from the other collaborator's perspective.

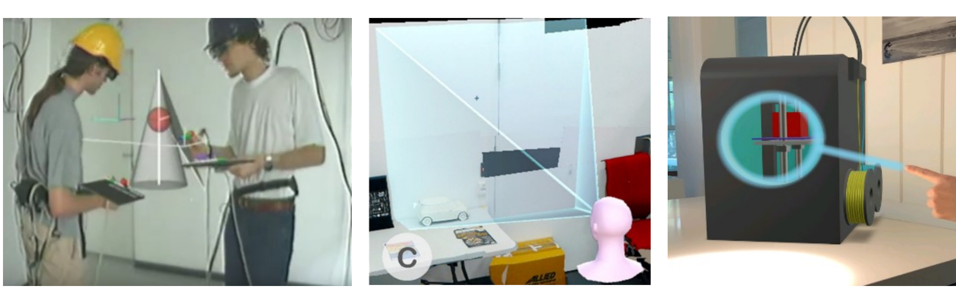

Figure 1. Left: Users share a common space with each other and the virtual content (© Hannes Kaufmann, [38]). Middle: View of a frustrum showing user's field of view (© Piumsomboon et al., [63]). Right: Dynamic layers showing behind an object, similar to [2].

4.1.2 Collaborators need to see each other's emotions. Sharing the workspace is not necessarily limited to sharing the physical properties of the space, and understanding others 'emotions plays a critical role in collaboration. AR HMDs cover a peer's eyes, and could interfere with nonverbal communication of emotional states [67]. Physiological sensors can measure and share participant emotional states. [19] displayed the real-time heart rate of the other player and played a corresponding heartbeat sound to increase the feeling of connectedness in a collaborative experience. Furthermore, although AR collaborators display less eye contact [66], this can still lead to higher confidence and trust in partners than without using AR.

4.1.3 Collaborators need to stay aware of the progress of synchronized tasks. When working on the same task, instant feedback helps collaborators adjust accordingly. For example, the color turning of objects can indicate successful attempts of the collaboration [63]. An arrow sign or exclamation icon can appear to indicate the moving direction or the status of a commonly-manipulated object [23] (Figure 2 right). [58] proposed a haptic communication system which uses vibration to convey simple messages like a positive sign, wrong selection or warning to provide instant feedback of the progress. [18] proposed an information panel on the corner of the view to show progress. When an augmented block is selected block, it is rendered in blink mode, so it is easy to be spotted.

4.1.4 Collaborators need to show/hide layers of the environment. Several studies highlight the importance of filtering layers of information during collaboration when users need to focus on a particular feature in the environment. To accomplish a task, users may need to inspect a segment of the environment in greater detail. To address this, [26]give users the ability to select individual data points in a visualization to filter the level of detail according to their individual needs. Similarly, [31] use cards to modify the way data is presented in a user's environment. For example, placing a "soil sensor" or a "hydrology card" changes the geospatial data visualization. [48,53] allow users to selectively hide the layers of the content so that people with diverse skills or roles can focus on a particular aspect of the same model. By hiding irrelevant information, users can accomplish collaborative exercises more efficiently without taking on an excessive cognitive load. On the other hand, by showing hidden information users can access relevant objects that are out of sight during collaboration (Figure 1 right). [2] addresses the need to view objects that are occluded from one or more users 'viewpoints by using "show-through techniques" which show items behind other items in the environment. These techniques are found to reduce the number of cases where users get very close to or bump into one another and led to increased spatial understanding.

4.1.5 Collaborators need to have information on demand. In addition to filtering through layers of information, users often need to actively collect a specific set of information about the environment in order to complete a collaborative task. For instance, users can use a magnifier feature to examine virtual data [32] or distant objects [48] in detail. Also, their natural actions can trigger information presentation, for instance, interactive gaze feature [63] only reveals a hidden number or letter when a user gazes at a block that is initially shown as blank. Several studies provide examples of information on demand, where users can visualize archaeological layers of the scene by interacting with a 2D display [7], listen to audio narratives about the artifacts in a museum by clicking on the associated virtual representation [29], find puzzle hints behind the collaborator as they interact with their partner's virtual avatar [97] or see the location of the next object that needs to be interacted by completing an action in a training scenario [89]. [40] find that by providing spatial information about the placement of an object, users experience decreased cognitive load and make fewer errors.

4.2 Collaborators need to be aware of the past

Awareness of the workspace is not limited to the present, but can extend to reviewing things that happened in the past.

4.2.1 Collaborators need to remember actions. Remembering the past is an important ability for collaboration, and at the simplest level, the system can track if specific actions have been achieved – for example in [8] users searching for items see small HUD icons tracking which items have been found. [27,49] created interactive environments where the full sequence of user actions and their effects can be recorded and played back later, by capturing a user's movements and changes to the virtual scene. Such recordings are valuable for instructions and training [95]. Such features also allow new users to review how the selected objects and the space has evolved in time up to its current state.

4.2.2 Collaborators need to remember conversations. In the system presented in [27], instructors or peers can record their conversation. Having a database of previous conversations can be useful for novices to remember educational content, or for peers to recall what was determined during a previous meeting. These recordings do not have to be audio, but can also involve text recordings such as in [15], or musical patterns[4].

4.3 Collaborators need to coordinate attention

During discussions, participants need to attend to the same objects and to redirect group attention to new items.

4.3.1 Collaborators need to specify direction of attention. Pointing gestures happen naturally when people try to draw other's attention to a specific location. Features have been designed for allowing collaborators to point at locations and share cues with local AR users in real time while highlighting the locations [36,53,85]. Another often presented feature is pointing with a colored ray from the index figure by using hand gestures [41,45,64,84,85,92]. Such rays can be expanded to include a bold dot at the end of the pointing ray to improve the visibility [64]. 2D device like tablet or PC users can point using mouse on 2D devices to show dots on AR videos [5,76]. [96] proposed the integration of Google Daydream Controller in a co-located AR environment to point with a virtual laser pointer at menu items from a 3DOF controller, which can also be considered for directing attention of peers.

4.3.2 Collaborators need to specify objects of attention. Users can emphasize or draw attention to a particular object employing a highlighting feature [37,69][69]. For example, floating webpages become highlighted when viewed by a user [37]. Another way to point and highlight part of an object is to cast a ray to connect a colored annotation card and a 3D model, causing animations when the two objects are touched by a user [69]. To enable users to point out an object more precisely, [6] proposed that when users interact with small objects, communication can be improved when users highlight objects by moving their fingers along the boundaries of objects, rather than simply pointing at small areas. Other than pointing and gesturing with bare hands, temporary icons such as arrow pointers are another feature to help users point in the AR environment. [55] proposed for users to use handheld devices with dominant hands to cast an arrow pointer. [3,13] both introduced an arrow pointer which can be left on a location guiding the collaborators, and participants can place warning signs to attract other workers attention to a specific location or a specific part of a machine [91].

4.3.3 Collaborators need to manipulate objects at the same time. When utilizing AR in cooperative settings, there is frequently a need for multiple users to manipulate the same virtual object at once, and it is therefore important that features exist to promote seamless simultaneous actions among collaborators. When concurrent input from multiple users is necessary or beneficial, features are often designed to require mutual input, meaning that an action is taken when multiple users attend to the same object. [61] explore how through hand and foot-based interactions, users have the ability to manipulate objects at the same time while using different modalities. [63] introduce a collaborative feature whereby two users looking at the same block to find the right object in a collaborative target search task. This shared gaze feature serves to ensure synchronized participation among collaborators and that there is a symmetry in the roles of users.

Mutual gaze features may be particularly effective when coupled with information about collaborators 'attention and actions, as user performance and subjective preferences were found to be maximized when virtual awareness cues were included. As an alternative yet related approach to support simultaneous collaboration, [35] introduce "bent pick rays", a collaborative technique for co-located multi-user interactions that is designed to provide continuous visual user feedback and keep users informed about the collaborative manipulation. As objects are manipulated by two or more users, pick rays are colored lines that denote the object that users have selected. When users select the same object, the object is moved by merging the input from both users 'hands, and pick rays bend so that they remain connected to the dragged object. This technique appears to facilitate simultaneous collaboration without restrictions (such as object locking) and could be implementable in Maker Space environments.

4.4 Collaborators need to coordinate instructions

Some collaborations involve the exchange of expertise, such as when a teacher is interacting with a student, or when a knowledgeable student is teaching a novice. During these contexts, the immersive environment can contain features that help the expert to guide a novice.

4.4.1 Collaborators need to annotate objects. Users may benefit from the opportunity to more permanently annotate or draw on objects (Figure 2 left). For example, [76] present participants in a block arranging tasks with the opportunity to virtually draw annotations on objects, which enables users to give spatial information about the placement of an object and reduces the cognitive load and user errors. This feature is accompanied by a cleaning tool, which allows users to completely clean the drawings in the working area to prevent overlaps, and an erase tool, which permits users to partially clean the working area or to undo an action. Through drawing annotations, users can leave notes in locations of interests [40], and this is sometimes encouraged through the implementation of shared whiteboard features [9], where a pen (or another tool) can be used to write and interact with the environment. [82] used textual annotations that move according to the user's viewpoint. By explaining different parts of complex models, these labels can help users remember important terms and relations between the parts of the system. [86] find that drawing in space facilitates communication through annotations; in some cases, these drawings can be triggered through gestures, such as lifting the thumb while pointing [41]. In certain conditions, drawing features are not only used to emphasize features of existing objects but are also applied to facilitate the creation of new objects. [30] present a Content Creation Server that is able to take raw drawing point data in order to recognize the drawing, and this content is then displayed as newly created virtual objects in the environment. There are therefore multiple potential applications of annotation and drawing features, although it is worth noting the potential fatigue of drawing in mid-air without support for long periods of time. As one solution to this, [30] propose two content boards: a horizontal drafting board that is utilized for annotation and drawing, and a vertical board with duplicated content that displays information for all collaborators to see.

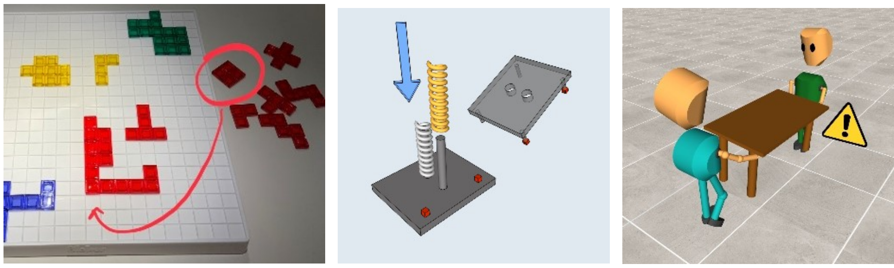

Figure 2. Left: Drawing annotations on real surfaces, similar to [40]. Middle: Icons showring the next step in a sequence of instructions, similar to [55]. Right: Icon showing if the table is balanced between two collaborators, similar to [23].

4.4.2 Collaborators need to guide others. Task guidance annotations about step-by-step procedures can be anchored to the environment as an approach to share information with others who may not be physically present, such as what next steps should be performed in a task [31,41,74,86,92]. Such annotations reduce cognitive load and errors [41]. Annotations can be in the form of labels or drawings that are fixed in place, and users who initiate the drawing or annotation can erase it with a button to avoid cluttering the space [86]. Besides drawing, users can also leave a marker on the virtual image as an annotation to guide the action of peers [54,55] (Figure 2 middle). The markers can be in a shape of square [55], dots [54], arrows or anchors [13]. [31] introduced a physical marker card to help share information among all the collaborators in a floating AR environment. Once this marker card is placed at a spot on a map, the system will look for information that is bound to the location and render a virtual model to the card. If users want to see the virtual model of a different location, they can simply move the marker to the new location. In addition, users can pick up the marker to further examine the augmented virtual model from different angles. Every collaborator is seeing the virtual object from their own angle.

4.5 Collaborators need privacy

Privacy and information asymmetry is an important consideration for virtual environments. Unlike real environments, two AR users can have different views of the same space, because different virtual information can be shown to each user. These features allow users to control what they see and how they share information with their peers.

4.5.1 Collaborators need personalized information. Some information can be visible to everyone but look different, depending on instructional roles. For example, when students are learning about electromagnetism while looking at an audio speaker, it is helpful for their learning to be scaffolded through representations that directly target their learning, for example only seeing magnetic fields or only seeing electricity [68]. However, when teachers look at the same physical object they may wish to have lots of information that will help them instruct students, along with controls for how to enable/disable information that students may see. In this sense, collaborators are seeing different information even when looking at the same physical object. An example of a personalized view of the same scene is dual-language support where each user sees the labels in their own language while interacting with the same objects together [96]. This is a very helpful feature for international groups of people working on a task collaboratively. Different visualization modes and filtering can also be used to choose different visibility per user. [39] used independent mode, collaborative mode, and teacher mode in an AR application for Mathematics and geometry education. In independent mode, students can only see their own version of the construction, which is invisible to others. This allows students to progress at their own pace without being influenced by other student's answers, which is a very useful feature for classroom settings.

4.5.2 Users need private space within a collaborative space. In a collaborative AR meeting, users may want to browse related content privately before sharing it with others, or for instance, they may want to freely sketch out their ideas before making it visible to other people. [75] allow users to first perform private editing and then make it visible to other users. Similarly, [8] let participants make an item visible to the other player after they spot it in the environment. [44] created a collaboration schema regarding the visibility of the content and identified collaboration scenarios including "Private AR with Shared Views" where users can share some of the content with others. However, if the content needs to be private temporarily, it could be hard for users to constantly change the visibility settings. [82] present a way to automatically manage privacy settings by layering information with different security statuses. They implemented their approach into a collaborative board game where the table is always visible for all participants, but one player's game-pieces are only visible to herself or himself. Once a tile is moved to the common tabletop region, the object inherits new security information and is rendered visible to everyone. They found that this technique provides ease of use, makes the application easy to learn, and fun to play. In some cases, privacy could be a must-have feature. For instance, in a multi-user experience, users may be asked to enter their password for certain actions and this can never be visible to all users. Private spaces are also used for avoiding clutter in the shared space. For instance, Toolbox UI menus providing easy access to collaborative tools [27] or Personal Interaction Panels (PIP) allowing personalized settings [38] could be visible to the owner only [82]. Having a panel or menu in front of every single user could make a mess in the scene. Therefore, making some components of the application not visible to everyone is as critical as maintaining a consistent shared state. Designers need to consider users 'needs and ensure privacy for improving the efficiency of collaboration.

4.6 Collaborators need to manipulate virtual objects

Creating or modifying virtual objects was a frequent feature in the papers reviewed. Although not a generic collaboration feature, we report this category due to its popularity in different kinds of collaboration scenarios. Sometimes collaborators needed to create virtual objects that are tightly coupled to real objects, such as when brainstorming how a physical object should be modified; and sometimes the representations were not coupled to physical objects, such as in the case of using a 3D model to design a brand new object. A variety of features have been designed for such creation tasks.

4.6.1 Collaborators need to move virtual objects. When collaborating in AR, a very common need is to move objects within the environment in order to accomplish a specific task. [13] introduce an object manipulation feature that allows users to pick up and place digital furniture in a home to test out various configurations. To facilitate seamless interaction, users are often given the ability to pick up and drop objects, including the option to pass objects between one another [8,31,70,78,79]. This object movement can be accomplished through a variety of modalities according to the task design, including the utilization of tools, controllers or handles [6,56,60,82,89]; in other designs, users are able move objects directly with their hands [30,56]. Although many studies involve multiple collaborators with the ability to move objects, in some cases a single user is responsible for the movement of objects and is guided by a collaborator [98]. Beyond basic grab and drop features, some studies integrate more complex means of object transferal. [82] introduce the concept of "face-snapping" during a study involving users playing Mahjong. In this experiment, as a user drags tiles with a pen, the requirements of the collaborative task are checked, and the highest priority need is automatically performed immediately. If a user releases a tile, it stays aligned with the other tiles on the board, as there is a need for precise feedback that the tile has been correctly placed. This kind of feature allows imprecise user actions to generate precise results. [21] present another original design to facilitate object movement, through the utilization of "crushing points" at the surface of the manipulated object. Each user selects a crushing point with a virtual 3D cursor, and the motion of the two users is averaged, enabling easy object transportation. Furthermore, [10] demonstrate that object movement can be extended to Tangible AR interfaces. The Tangible User interface permits users to play, remix and modulate virtual musical elements by picking up and manipulating real objects in space, such as records, and users are able to modify music and sounds by translating the records up and down. Notably, in some circumstances it may be useful to set constraints on object movement; for example, in order to ensure that furniture items are only placed on the floor, [13] fix the z-axis so that items are located at the same level. Within Maker Space environments this may prove useful when a collaborative endeavor requires anchoring to a particular surface (such as a floor or tabletop).

4.6.2 Collaborators need to modify virtual objects. In addition to enabling object movement, there often exists a need to adjust the scaling of the objects within a given environment. Through virtual object interaction, users are able to control the position and orientation of a virtual object and accomplish tasks involving object rotation, and scaling [69,72]. As with object transfer methods, multiple means can be used to accomplish scaling, and optimal approaches may vary across collaborative exercises. [38] presents an object modification technique whereby users can move a point lying on a sphere in order to adjust the sphere's radius. In a study by [90], users rely on gestures in order to instantiate and scale an object, which assists with the selection and manipulation of objects at a distance. [30] introduce an interactive 3DSketch interface with a pie menu that shows operation options including copying, rotating and scaling. Additionally, users may wish to "capture" a digital object from the scene in order to resize or morph into another shape; [32] accomplish this by allowing users to select an object to fit into a cylindrical volume for convenient interaction and cooperation. In AR Maker Space environments, real-world objects may not be easily scaled, and so existing studies have focused on scaling digital objects; further studies might explore whether real-world objects could be digitally replicated in order to benefit from increased flexibility in scale and positioning.

4.7 Collaborators need to share the same environment

Finally, a fundamental need is for users to share the same environment. While performing group activities in AR, collaborators inhabit an environment with their peers, which includes both the physical space as well as the virtual space. In this section we discuss features for achieving the basic needs of collaborators needing to share the space with their collaborators. Unlike the previous features, these are features of the environment rather than user interactions, but their design needs to be considered for supporting collaboration in AR environments.

4.7.1 Collaborators need to see the same virtual content. In general, performing activities in a virtual environment requires collaborators to see the objects they are collaborating around, and to sense the presence of their collaborators. In collocated settings where participants use AR, collaborators can see each other's physical bodies and the physical objects in the workspace, but virtual objects need to be synchronized between devices. At the most basic requirement, the dynamic properties of virtual objects (such as movements and changes in shape) need to be synchronized (Figure 1 left), but in larger collocated environments, it is helpful to have features for sharing audio and possibly video communication so distant participants can be aware of each other. To achieve this, systems require network connectivity for sharing object and body positioning information, and possibly information about the features of physical objects [74,83,92].

4.7.2 Collaborators need to have a smooth networked experience. Network communication is influenced by transmission delays and packet loss, and reducing the transmitted data is an active field of research, and collaborative applications usually employ signal smoothing to avoid jittery movements of virtual objects [56]. Even if high bandwidth communication is available, simplification is sometimes valuable, for example in measuring eye gaze [26,46,63,80], it is usually not necessary to share high-frequency eye movement saccades between users, and smoothing is preferred by users. [63] describes further methods to simplify data transfer between collaborators, for example local users having their virtual hands fully animated while seeing their collaborator's hands in pre-defined hand poses, such as pointing, grasping or thumbs-up. Although such features may not be necessary for small space collocated AR experiences, they may be useful for larger spaces where participants can see virtual collaborator bodies from a distance. Such simplifications reduced network bandwidth while maintaining communication.

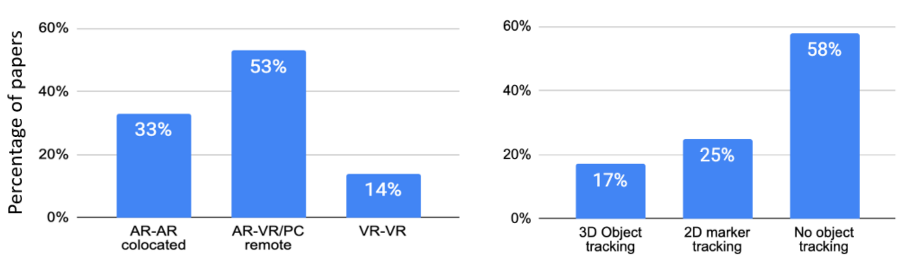

Figure 3. Left: Percentage of papers where collaboration occurred under different hardware configurations. Right: Percentage of AR papers using different kinds of tracking technologies.

5 DISCUSSION

In this review of existing AR and VR literature, we have collected the generic collaboration features that can be applied to support headset-based collocated AR experiences, and identified the needs that underlie these features. An area identified for future growth is collaborative features integrated with physical objects. While some of these features show virtual content attached to the users (e.g. laser pointers from a user's hand), others show virtual content that is attached to physical objects in the environment (e.g. drawings on a physical object). In order for the latter features to work, the headset-based sensors must be able to properly detect and track physical objects. Accurate object tracking in the real world is highly desirable in AR, especially in places like maker spaces and industrial settings where users need to interact with many different physical objects; however, detecting and tracking physical objects is a challenge. In our review, of the papers that involved AR, 17% of papers involved tracking real objects, while 58% did not augment any items, and 25% augmented planar surfaces such as printed papers (Figure 3 right). This biases the features observed towards features that are not anchored on physical objects. Precise tracking and understanding of 3D physical objects is possible with technologies such as Deep Neural Networks, however, they are energy-heavy [1]. Also, they require large amounts of memory and CPU [33]. Software like Vuforia Engine provides software that enables developers to scan a 3D object [24] or use a CAD-based model to use as a target for their AR application. However, for good results, the target objects have to be rigid, non-flexible, should have enough geometric complexity, and preferably be in multi-color contrasting the background. Also, for better tracking, these objects should not be moved after detection. All these challenges currently restrict the development of features that integrate virtual content within the physical environment. It is expected that in the near future, as headset-based devices collect data about users' environments with evolving spatial sensing hardware, more features will be developed to aid collaboration around physical objects. Future work could expand this review to other AR devices beyond headsets, such as handheld mobile devices with 3D scanning capabilities. Even though the interactions with such devices are different than headset-based interactions, due to the fact that users must use their hands to hold and interact through screens, this literature may reveal other collaborative features that leverage information about 3D physical objects.

Another area for future growth is remote assistance. Although the emphasis of our primary research question concerns collaboration using augmented reality within co-located maker space settings, our literature review included multiple papers discussing remote collaborations. Across the studies analyzed, 33% took place purely through collocated AR collaboration, and 53% involved a local AR user collaborating with a remote user (either working through VR or PC), while the remaining 14% were VR-VR collaborations (Figure 3 left). Features from remote collaboration were used for this review since they can apply to collocated settings, for example the feature of seeing a remote user's viewing area [63] is also valuable for understanding collaborator attention in collocated settings. Other features for viewing remote collaborators, such as seeing the other person's other's location, head rotation, hands and body movement (e.g. [45,93,97]) may not be applicable to small space AR collaborations. However, in the future when AR headsets are designed for large-scale collocated collaborations, these features will become more prevalent to increase connection with distance collaborators.

Finally, we acknowledge there are other features that could be designed to fulfill the needs identified in our review, but which have not been observed in the papers we reviewed. For example, we have determined the need for collaborators to remember the past, and presented features that could satisfy this need. This need could also be fulfilled with other features, such as shared checklists to track completed tasks, or a heated map feature which shows different colors after both collaborators have discussed specific parts of a learning environment. [62] proposed heat map feature through eye tracking in single-user AR environments, which could be further explored and adapted for showing collaborative activity in multi-user environments, collected from eye tracking or hand tracking. This points to the possibility that there are features designed for single users which have not yet been tried in multi-user environments. Additionally, there may be collaborative features that could be transferred from/to other domains such as tabletop tangible interfaces (e.g. tracking multiple user's head gaze to increase awareness of attention), or screen-based video games (e.g. using the idea of bent pick rays [35] for collaborative object manipulation in 2D multiplayer drawing games). We also acknowledge there are needs that we have not identified because they are not present or easily visible in existing AR/VR collaborative interfaces, such as the human desire to care for another living being [65]. Expanding the review criteria to papers that do not discuss systems, or that discuss single-user narratives or gameplay experiences, could reveal other social interaction needs that may be supported through AR features.

6 CONCLUSIONS

In this literature review we generated a list of features that can support collaborative needs in AR settings where collocated users wear headset devices. To achieve this, we surveyed 92 studies of AR and VR collaborations, collecting 18 categories of features that can be designed into AR systems. These features meet a spectrum of collaborator needs ranging from more passive features, such as collaborators needing to embody a shared environment, to more active features such as methods for directing collaborator attention, to complex needs such as needing to create objects at the same time.

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