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Physicality as an Anchor for Coordination: Examining Collocated Collaboration in Physical and Mobile Augmented Reality Settings

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Design and co-creation activities around 3D artifacts often require close collocated coordination between multiple users. Augmented reality (AR) technology can support collocated work enabling users to flexibly work with digital objects while still being able to use the physical space for coordination. With most of current research focusing on remote AR collaboration, less is known about collocated collaboration in AR, particularly in relation to interpersonal dynamics between the collocated collaborators. Our study aims at understanding how shared augmented reality facilitated by mobile devices (mobile augmented reality or MAR) affects collocated users' coordination. We compare the coordination behaviors that emerged in a MAR setting with those in a comparable fully physical setting by simulating the same task – co-creation of a 3D artifact. Our results demonstrate the importance of the shared physical dimension for participants' ability to coordinate in the context of collaborative co-creation. Namely, participants working in a fully physical setting were better able to leverage the work artifact itself for their coordination needs, working in a mode that we term artifact-oriented coordination. Conversely, participants collaborating around an AR artifact leveraged the shared physical workspace for their coordination needs, working in what we refer to as space-oriented coordination. We discuss implications for a AR-based collaboration and propose directions for designers of AR tools.

CCS Concepts: • Human-centered computing • Collaborative and social computing • Empirical studies in collaborative and social computing

KEYWORDS: Augmented Reality, Collocated Collaboration, Co-Creation, Virtual Artifacts, Physical Artifacts

ACM Reference format:

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1 INTRODUCTION

Design and creation activities often require close collaboration between multiple stakeholders. Such collaborative creation processes tend to be most effective when all core actors are physically collocated [62]. A shared physical space and artifacts provide a distinct set of affordances to promote collaboration. Collaborators can move around the artifacts of work, using them as coordination aids to organize and structure the work [23].

Also, collocated users are able to leverage the shared physical workspace as an additional mechanism for coordination. Particularly, the information transmitted by one's position, posture, or movement in the shared space serves as a primary mechanism of coordination between the collocated collaborators [21, 59]. Furthermore, a collocated environment naturally supports deictic referencing and gestures to help coordination [50, 94]. Therefore, traditionally, physical workspaces are used to facilitate the collaborative design process, employing shared artifacts such as whiteboards, mockups, models, and prototypes [64].

Notwithstanding the advantages of physical spaces and objects, using digital or digitally-enhanced environments, tools, and artifacts can benefit collaboration. Digital artifacts are easier to create, reproduce, and modify when compared to physical objects, thus reducing the constraints on designers' creativity. The malleability of digital artifacts can significantly speed up rapid prototyping stages, as the digitally represented artifact of design can be continually manipulated and adjusted.

Combining the affordances of both digital and physical mediums, shared augmented reality (AR) may be well suited for supporting a range of collocated design-oriented tasks. On the one hand, AR retains a physical medium's inherent advantages for collaboration because it embeds digitally rendered elements into the users' physical 3-dimensional (3D) environment, supporting the ability of the users to leverage the physical space for their coordination. In addition, AR may partially retain natural interaction mechanisms, enabling users to relate to the virtual artifacts as if they are physical entities situated in the physical space. On the other hand, AR supports the creative advantages associated with the digital medium, particularly the versatility and changeability of digital objects. Using AR may reduce the waste of physical resources and promote rapid iterations and changes in the artifact of work, expediting creative tasks such as design reviews, collaborative prototyping, and modeling. Notwithstanding these advantages, AR has some limitations when compared to fully physical environment. For example, in AR, a user's actions and intentions may be more difficult to infer and interpret, since using AR head-mounted displays, tablets, and other devices may obstruct the information about the collaborator's perspective, intentions, focus, and gaze. Thus, the use of AR may hinder mutual awareness of each other's actions and intentions, possibly hindering coordination.

Research of the ways in which AR technology can support different kinds of collaborative activities is particularly timely as mobile devices continue to democratize access to AR technology [38]. Mobile augmented reality (MAR) is the most popular consumer-level AR form-factor accessible to all smartphone and tablet users. It is not uncommon nowadays to see smartphone holders all over the world gathering together to create virtual artifacts at the same physical locations or play MAR games experiencing the same virtually augmented world together[1].

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[1] https://www.theverge.com/2019/11/6/20950615/niantic-pokemon-go-live-multiplayer-ar-augmented-reality-buddy-adventure

The ongoing spread of MAR motivated our exploration of its ability to support collocated collaboration. We investigate how collocated users coordinate their actions and behaviors in both MAR and physical environments in the context of a design task involving the co-creation of a 3D artifact, similarly to other studies on collaboration in mixed reality [31, 46]. Using a controlled laboratory study that entails the design of a structure out of singular square blocks, we compared how participants collaborate in a completely physical and an augmented reality environment (Figure 1a-b). The task and the setting for each experimental condition were made similar. The participants worked around a physical worktable, on top of which the participants had built the structure. In the fully physical condition, the participants used actual wooden blocks. In the AR condition, the participants used digital blocks and placed them on top of the physical surface (table) using handheld tablet computers.

Figures 1a-b: A pair of participants working in the Physical (left side of the picture) and the AR (right side of the picture) conditions, in both conditions using Minecraft-like blocks.

Our findings demonstrate how the physical space and artifact affected participants' coordination-related behavioral patterns. Namely, we show how in the fully physical setting, the collaborators mostly adopted an artifact-oriented coordination approach, by focusing their coordination around the artifact they were building, actively referencing it and its specific parts, and building the artifact's elements together. Conversely, we show how when using MAR, the participants mostly adopted a space-oriented coordination approach, by dynamically moving around the physical space of work, building different parts of the artifact separately, often changing positions around the workplace, and working physically close to each other. Interestingly, despite the differences in collaboration patterns, the participants' user experience was quite similar across the experimental conditions, apart from the perception of collaboration quality, which was higher in MAR.

The paper continues as follows. First, we describe prior work on collocated collaboration both in physical and digital environments. Next, we describe the methodology of the experiment. The results are then presented, first describing the differences in coordination-related behaviors between the two conditions followed by participant's subjective perceptions. Finally, we discuss our results in light of previous works followed by the limitations of our study and future research suggestions.

2 PRIOR RESEARCH ON COLLOCATED COLLABORATION

Our work focuses on collocated collaboration. Thus, we first review physical collocated collaboration in design work that uses a shared workspace with shared artifacts. We then review works that used various digital workspaces to support collocated collaboration. Finally, we discuss the use of augmented reality solutions in this area.

2.1 Collocated Collaboration in Physical Design Environments

In various application areas, such as architecture, engineering, and industrial design, work is commonly done in a collocated collaborative manner with multiple stakeholders providing their input. Such tasks can be described as being tightly coupled [32], as the collaborators work together closely, as opposed to independently. In such conditions, the success of the work largely depends on participants' mutual awareness – the up-to-the-moment understanding of another person's interactions with the shared workspace [33]. High degree of mutual awareness entails the collaborators' ability to coordinate their work and to be constantly aware of what the others are doing and thinking during the work process [25]. Beyond verbal communication, collaborators' coordination-related behaviors include non-verbal communication, such as deictic references [12, 26, 29], as well as joint manipulation of the design artifacts created in the process of work [3, 11, 66]. In addition to users' explicit communication, the shared physical workspace also increases mutual awareness of the collocated participants [25, 50]. Namely, the positions of the participants, their posture, and movement around the space serve as an important source of coordination-related information [21].

The intermediate design artifacts can also serve as a means to coordinate the collaborative work. Such artifacts often have symbolic nature, for example, design storyboards and paper sketches. However, they can also be the objects of design itself, such as physical mockups, models, or prototypes [64]. Existing works describe how tangible mockups in collaborative design practices help designers to enhance direct interactions and conversations by letting them engage their senses during the shared work [11, 14], serving as the representation of shared objectives, and grounding mutual understanding of work progress. Such mockups are described as things-to-think-with [47] and can be viewed as a form of the collaborators' shared extended cognition, acting as a critical coordination aid [41, 64].

2.2 Collocated Collaboration in Digital Workspaces

The shared artifact of design may be physical or digital. A 3D physical artifact such as a model or 3D mockup has the advantage of allowing direct interaction through gestures and non-verbal behavior. However, physical mockups lack flexibility and are often difficult to manipulate, annotate or reproduce. Therefore, various studies in the fields of engineering and construction [27, 55, 65], architecture [20], and industrial design [42] explored the viability of digital technologies for supporting co-design of digital artifacts.

As was discovered, the lack of a shared physical workspace and the inadequate support for natural coordination mechanisms, reduce mutual awareness of the users and negatively affect collaboration in digital spaces [97]. Thus, a substantial body of works in computer-supported cooperative work has focused on exploring various coordination mechanisms in collocated computer-mediated collaborative environments. Specifically, much work in this direction has been made in the fields of groupware systems for shared workspaces [32, 33, 60] and tabletops [56, 85, 93, 102].

The development of tabletop groupware systems allowed to introduce the dimension of physical space to computer-supported collaboration, at least to some extent and for some tasks. Subsequently, research on tabletops had produced a considerable amount of knowledge on how collocated participants manage and utilize the physical workspace for coordination [85, 94]. Importantly, it was discovered that, when working with tabletop computers, the participants use their position around the table to coordinate their task allocation behaviors [51, 93]. When the participants could change their position to work face-to-face, as opposed to being located shoulder-to-shoulder, their participation was more equal [56]. The size of the physical work area (e.g., the size of the tabletop) had also been found to directly affect collaboration [82]. The smaller the area, the more difficult it was to make physical actions and deictic references during the work [102], which increased the amount of verbal communication and decreased awareness and task allocation.

Still, shared tabletops cannot fully support collocated collaboration with 3D artifacts in ways comparable to working in entirely physical environments, because rendering three-dimensional artifacts on two-dimensional screens does not enable the same affordances for such artifacts' presentation and manipulation. One of the proposed solutions is to combine interactive tabletop systems with tangible physical 3D blocks that represent artifacts of design or their elements [19, 24, 30]. This setup, however, reintroduces the limitations of the physical settings into the collocated design and is suitable only for specific use cases, making it less attractive as a universal 3D design solution.

2.3 Collocated Collaboration in Augmented Reality

Some of the early works on collaborative AR demonstrated that shared AR technology that displays virtual artifacts within the user's physical space [87] can support collaborative design processes [77, 78, 91]. Moreover, collocated collaborative AR may be a particularly effective solution for collaboration in the context of 3D artifacts' creation [7, 8, 31]. Users can see virtual artifacts aligned with the physical world through a handheld device, in which the virtual artifacts are added to the camera feed [18] or through a head-mounted display (HMD) in which the augmentations are projected onto the glasses [8]. The virtual artifacts are superimposed on top of the physical workspace and are constantly adjusted to the changing angle of view of the collaborators and the changes in their immediate environment [2]. As such, AR and its multiple form-factors may combine the benefits of both digital and physical realms [75]. On the one hand, it affords the increased flexibility of virtual artifacts. The users can quickly produce design iterations, manipulate, change, review, and annotate virtual objects, and the changes in the virtual layer will be rendered in real-time for all participants [31, 81, 97]. On the other hand, collocated AR places the virtual artifacts in the 3-dimensional physical workplace, possibly affording the types of natural coordination behaviors that are associated with being physically present at the same place [17, 22, 48]. Particularly, the position of the users relative to each other, as well as gestures and other non-verbal cues, make sense only when the participants can relate these cues to a shared physical space [17, 48].

Notwithstanding its advantages, research on collaborative AR had also identified some obstacles and issues that may impede collaboration. At least for some tasks, the users may have a reduced ability to infer each other's actions as they lack a single shared view of the workspace [54, 100]. Moreover, collaboration in MAR has been associated with high mental load and frustration due to reduced efficiency and ergonomics of producing deictic gestures and increased cognitive costs of interaction [100]. Wang and Dunston [99] had come to somewhat different results in their evaluation of an MAR system for collaborative design review tasks. The authors found that the participants required significantly less time to complete the review task in AR compared to a pen-and-paper setting. The MAR system had enabled the participants to offload some of the cognitive effort associated with using traditional design review techniques [57, 99]. Still, the drawbacks of were also apparent. The participants experienced less physical comfort using the MAR system and assessed the interaction as not very intuitive or natural. The participants generally expressed their preferences for a fully physical setting stating that it would better facilitate their communication [99].

While several cases of collocated face-to-face AR collaboration had been explored in the context of learning experiences [43, 95], games [36, 103], technical drawings' inspections [16, 97, 98], and other contexts [34], the majority of the research so far focuses on remote collaboration [53]. It remains unclear how AR environments, particularly those facilitated by mobile devices, can shape and support collocated collaboration and group interaction [100] around design and modeling. Moreover, there is a gap in the academic knowledge of communication processes in collaborative AR in general [6] and collocated AR in particular [100]. With collaborative MAR technology being mature enough to focus on users' needs, experience, and interaction design [22], we aim to fill this gap.

2.4 Summary and Current Research

To summarize, when looking at technology to support collocated design collaboration, there is a choice between the fully physical workspace on the one hand and the digital workspace on the other. Evidence shows that collaboration in physical environments benefits from collaborators having a shared physical workspace and facilitating non-verbal communication [11, 32, 50]. However, such workspaces are likely to suffer from the limitations of the physical world - artifacts can be difficult to change, reproduce or iterate on. Augmented reality may prove to be a good compromise for collocated design collaboration, combining the benefits of both physical and digital realms. However, to date, the research of AR-assisted collaboration produced mixed results regarding its effect on collaboration and coordination, highlighting the need to better understand how AR affords and constrains collaboration compared with traditional fully physical settings.

The goal of the current study is to investigate collocated MAR environments in the specific task of collaborative design of 3D artifacts. In particular, we seek to understand how users coordinate their activities and task allocation in shared MAR in the context of co-creation activities. Synthesizing the previous works on coordination of collocated participants in organizational science, CSCW, and HCI, we specifically focused on identifying the *task allocation* styles of the users [32, 51], *deictic gestures,* and other non-verbal expressions [29, 46, 100], as well as positions and movements of the users around the workspace [21, 93]. We compare the emerged coordination behaviors with those produced in fully physical settings answering the following research questions:

- RQ1: What coordination behaviors emerge in a collocated design task of a 3D artifact in a shared MAR workspace?
- RQ2: What coordination behaviors emerge in a collocated design task of a 3D artifact in a fully physical workspace?
- RQ3: What are the differences between the coordination behaviors that emerge in an MAR environment as opposed to a fully physical environment?

3 METHODOLOGY

For our study, we adopted the observational informative study approach [15], designing a controlled user experiment in which participants were asked to co-design and co-build a structure in two distinct *conditions* using similarly looking square blocks:

1. The Physical condition, where the participants collaborated in building artifacts together, placing real wooden blocks on top of the physical table,
2. The MAR condition, where the participants collaborated in building artifacts together, placing virtual blocks on top of a real physical table, seeing the augmented environment through a tablet's screen.

3.1 Participants

Participants were invited to arrive in pairs to take part in the experiment. The participants were recruited via the University's experiment recruitment Facebook page and via printed ads distributed at the University's campus and nearby environments. Participants were paid the equivalent of 15 USD each for their participation in the experiment.

Overall, forty-six (46) participants participated in the study in twenty-three pairs. All participants in pairs have known each other before the experiment. Participants came with diverse cultural, demographic, and occupational backgrounds. The participants came from diverse countries of origin, including Brazil, Australia, South Africa, the US, Kazakhstan, China, Israel, and Ukraine. Twenty-six of the participants were females. The average age of the participants was 30.8 years old (SD=9.5). The majority held at least a bachelor's degree, with only two of the participants having only a high school education. Most of the participants were fully employed in various fields that included education, software engineering, design, law, sustainability engineering.

The experiment attracted participants with mostly high computer proficiency. All participants with the exception of two actively used personal computing devices daily. Thirty-two participants self-reported that they play video games on their personal computers, mobile phones, or consoles. Nine of the participants indicated that they played with less than weekly frequency, 8 participants indicated that they played weekly, and 15 participants indicated that they played with more than weekly frequency[2]. Twenty-two participants indicated that they played visually intensive games where they have to actively navigate in rich 3D virtual environments.

The participants' experience with augmented reality applications was more limited than their experience with virtual environments. Overall, twenty participants attested that they had experience with mobile apps that include light AR elements at least once[3]. Thirteen participants indicated that they used such apps with less than weekly frequency, 4 participants used them weekly, and 4 participants reported that they used them with more than weekly frequency.

3.2 Experimental Task and Setup

Inspired by prior work that explored coordination in mixed reality settings (e.g., [31, 46]), each of the conditions in our study involved building a specific type of structure out of singular square blocks equal in size. Our rationale for choosing the objects to build was guided by the existing studies on design and architecture outlining the importance of the physical space and artifacts of work in the creative design processes (e.g., [23, 76, 90]. Consequently, we chose to focus on enacting similar tasks of creating building models in augmented reality settings. Following several rounds of brainstorming and self-experimentation, we found three building types that have a reasonable balance between being abstract and specific, namely: *a city hall, a house, and a castle*. While still being open to interpretation, the participants were most likely to be able to imagine and visualize these structures, making them well-fit for use in our study.

Thus, within every condition, the structure that the participants were instructed to build alternated between three different types: a city hall, a house, and a castle. We did not provide any visual examples or representations of possible buildings for reference in order to avoid biasing the participants toward any specific type of collaboration or creation style. Instead, we kept the task open to the participants' interpretation by verbally instructing them that they could build the structure however they wanted,

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[2] Some of the examples the participants provided were Doom, Fortnite, Minecraft, Animal Crossing, Zelda Breath of the Wild, and Call of Duty Warzone.

[3] Among the applications that the participants used were *Snapchat* and *Instagram* augmented stickers.

according to their own vision and imagination. We also explained that during the task, they could freely talk, walk around, and collaborate in ways they deemed appropriate.

The experiment was conducted in a laboratory with a large table at the center of the room. The lab was equipped with four cameras, recording the work and interaction from four different angles. In addition, a separate voice recorder was set up to capture participants' dialogues. Two researchers facilitated the study, with one researcher engaging with the participants and the other observing from the side, taking notes and memos, and identifying interesting or unusual moments in users' interactions.

For the MAR condition, each participant was given an iPad device which she or he held and used during the session. We used existing software that enables the users to collaboratively build virtual artifacts out of blocks[4]. The software allowed the users to work in a shared environment, placing virtual blocks directly on the table. The participants saw the augmented environment as a see-through video on the screen of their device, looking at the virtual content by rotating and moving the device to control what is being displayed on the screen - a typical way to interact with mobile-based AR content [74, 88]. The application UI featured two soft buttons: one for placing the blocks and one for deleting them, and a crosshair in the middle of the screen. The participants aimed their device indicating where they wanted to put the block and pressed the corresponding button to execute the desired action. The MAR environment was synchronized such that each user could immediately see all actions of the other user. In the Physical condition, they were given 300 wooden blocks, each 5 cm in size on each side. The virtual blocks in the MAR condition looked similar to the physical blocks in the Physical condition. The blocks in both environments had identical textures and were approximately the same size.

In each experimental condition, the participants began the experimental task with having their own set of distinctly textured and colored blocks: one participant had the green-colored blocks, and the other participant had brown-colored blocks. Figures 1a-b demonstrate the participants working in each experimental condition.

3.3 Procedure

Upon entering the lab, the researcher explained the goals of the experiment to the participants, and they were informed that the experiment was recorded on video and audio. Participants then signed a consent form. Next, the researcher invited the participants to fill in the pre-experimental questionnaires, which captured their demographic characteristics, general computer- and MAR-specific proficiency, including their gaming experience, and their level of acquaintanceship. Participants then proceeded to conduct the experimental sessions.

The MAR experimental session began with a training session. The goal of the training was to teach the participants all available functionality in the software and make them feel comfortable with its interface. The researchers first explained each element of the

[4] We used the application WrldCraft available for free download in Apple's App Store at the time of the study

interface and then demonstrated each function available to the participants, such as: how to place the block, how to delete the block, and how to move around and view the created blocks from all sides. The researchers requested both participants to repeat all actions after them and then asked them to perform a test task, which consisted of each participant building a straight vertical column, create a horizontal extension for the column, and finally delete everything they have built. The experiment proceeded only after everyone was able to perform the test task and stated that they are feeling comfortable with the software and are ready to proceed. The training session's length was approximately 5 minutes long.

When the researchers were sure that everyone understood how to operate the equipment, the participants proceeded to perform the first experimental condition, which consisted of building one of the structures as described earlier. Each experimental session was limited to seven minutes. Upon completion of each experimental session, the participants were directed to fill in a set of post-session questionnaires assessing their experience in terms of creativity, fun, quality of outcomes, and easiness of work (described in the next section). Upon completion of both sessions, the participants filled a questionnaire comparing the experimental conditions on a range of parameters. Finally, the researchers conducted a semi-structured interview with the pair of participants. The order of conditions was fully counterbalanced within groups, in terms of both the type of structure and the type of interface (Physical, MAR).

3.4 Measurement of Participants' Perceptions

Prior to the experiment, the participants filled in demographic questionnaires, indicating their age, gender, academic degree, and occupation. After each experimental session, we measured the following constructs, using the existing questionnaires:

1. User experience, using User Experience Questionnaire (UEQ) by Laugwitz, Held, and Schrepp [49],
2. Subjective assessment of collaboration, using 3 adapted items from Collaboration Satisfaction Measurement Scale by Judith [28],
3. Perception of structure quality, using the sub-scale of well-craftedness from Creative Product Semantic Scale (CPSS) by Besemer [5],
4. Work creativity, using Creativity Assessment Scale by Oldham and Cummings [61].

At the end of all experimental sessions, we asked the participants to compare what condition was the most creative, effective, easy, and fun, using the appropriate items from the user experience questionnaire by Laugwitz and colleagues [49].

3.5 Data Analysis

Due to a malfunction in the video equipment, four recordings were lost, allowing us to use the video analysis data from only 19 pairs. We were still able to include all 46 participants in the analysis of their questionnaire answers and interviews.

We analyzed video recordings of the participants using the qualitative thematic analysis guidelines by Braun and Clarke [13], adapted for video analysis by Suchman and Trigg [89]. First, the videos were imported to a qualitative analysis software (Atlas.Ti). Two researchers coded the first half of the videos together, identifying major events, noting initial thoughts on interesting video segments, and creating a rough content diary. Field notes from the observations were also used at this stage to help inform the initial coding categories. The researchers primarily focused their effort on analyzing body positions, gestures, and positions of the participants, as well as noticing the way the participants talked, moved, and interacted with each other and the devices. After identifying the key events and phenomena around collaboration and coordination in the videos, the subsequent coding passes were driven by iteratively refined coding schemes based on further studies of the videos. During the coding process, the researchers discussed any uncertainties and irregularities.

Qualitative video analysis was supplemented by the statistical analysis of differences in coordination and subjective perceptions of the participants. The quantitative data on the observed coordination behaviors was normalized and the differences between the experimental conditions were analyzed using paired-samples t-tests. The differences in the participants' subjective assessments of each experimental condition captured by the questionnaires were analyzed using Wilcoxon non-parametric test for two related samples.

Next, in the Results section, we provide a detailed description of the events and the emerged themes and explain how different experimental conditions led to different coordination-related behavioral patterns.

4 RESULTS

4.1 Coordination-Related Behaviors

From the video analysis, we observed and documented the major ways in which the participants coordinated their activities and identified key differences between the participants' coordination behaviors in each experimental condition. We describe our findings in detail in the following subsections.

4.1.1 Task Allocation Style

Task allocation style refers to the way the participants divided the work between them during the co-design process. In our observations, we identified two main styles of task allocation (demonstrated in Figure 2):

1. Task allocation according to different areas of physical space, working on different parts of the structure. For example, we observed how sometimes the participants built different walls of the structure separately from each other, based on where they were currently standing/sitting in the workplace,
2. Task allocation according to the same functional element of the structure, complementing each other's input. For example, sometimes, the participants

worked on the same wall of the structure together, with one of them implementing the wall itself, and the other one simultaneously creating a hole in the middle of this wall to make a place for a window in this wall.

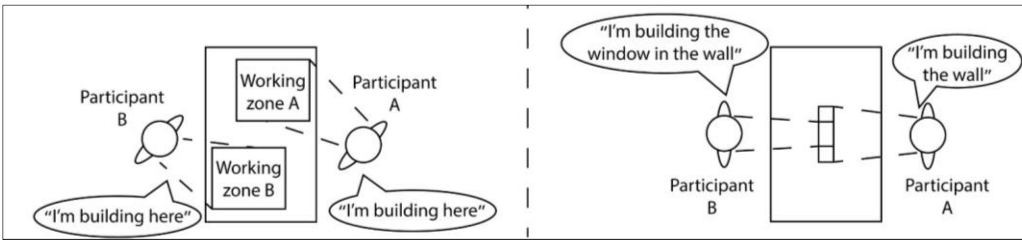

Figure 2: Schematic representation of different task allocation styles, with the participants dividing the work according to different areas of physical space (left), and building the same elements of the artifact together (right).

We measured the time that the participants spent in different task allocation styles, either devoting their time to building different elements of the structure in different places in the physical workspace (i.e., different areas) or building the parts of the same parts of the structure (i.e, same element). The average total amount of time per session spent allocating tasks in different areas was 128 seconds in the Physical condition and 301 seconds in the MAR condition. This difference was significant (t=7,77 p<0.001). The average total amount of time spent building the parts of the same elements was 161 seconds in the Physical condition and 74 seconds in the MAR condition. This difference was also significant (t=4.37, p<0.001). The average time spent by the participants in each allocation style in both experimental conditions is summarized in Figure 3.

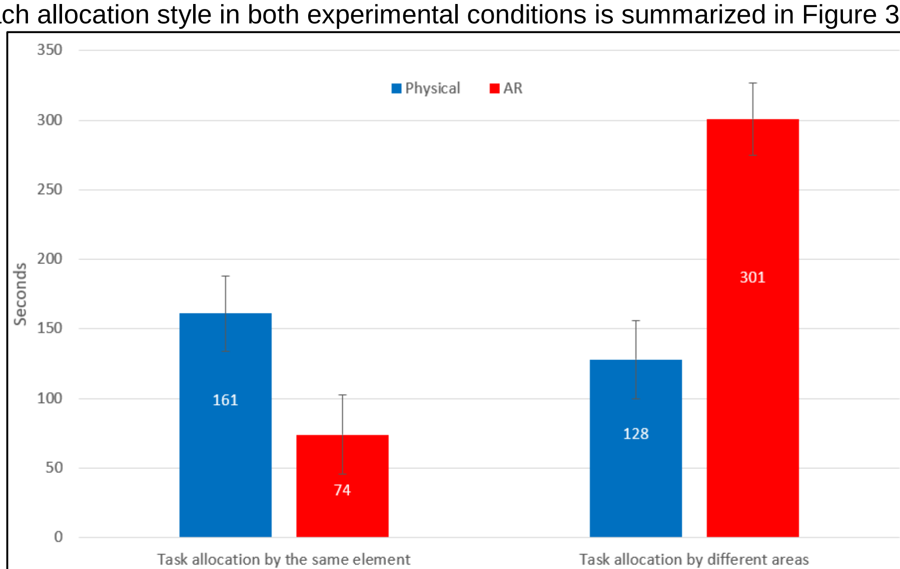

Figure 3: The average time in seconds spent by the participants in each task allocation style in the AR and the Physical conditions

Overall, these comparisons indicate that the participants preferred working in different areas of the workspace in the MAR condition while spending much more time working on the same elements of the structure together in the Physical condition.

The differences in the participants' task allocation behaviors could be explained by the natural richness of communication available to the participants in the physical condition, enabling them to effectively coordinate around small details of the artifact. When directly observing the participants' behavior in the Physical condition, we noticed how the participants could easily adjust to each other's actions and predict each other's intentions leveraging the natural richness of communication available to them. They watched each other's body movements (e.g., a participant reclining forward to focus on a specific part of the structure), inferred each other's gaze by looking at their partner's face, and tracked each other's hand movements in the Physical condition. Consequently, the participants were able to easily focus on the same parts of the artifact and flexibly complement each other's activity. Contrastingly, in the MAR condition, the participants mostly looked at their own tablets and tried to infer where their partner was working by looking where the new blocks were added to the structure. This form of coordination arguably allowed a less fine-grained understanding of each other's actions and intentions, resulting in the collaborators' overall preference to focus on different areas to avoid interfering with each other's work.

Figure 4 shows concrete examples of participants working in different styles of task allocation in the two experimental conditions. As seen in the figure, in addition to directly viewing the participants' behavior during the observations, in the MAR condition, the character of task allocation can be inferred by the placement of each participant's uniquely textured blocks during the work. In the task allocation by different areas, different types of blocks are being placed in separate areas, while in the task allocation by the same element, different types of blocks are interspersed within every structural element.

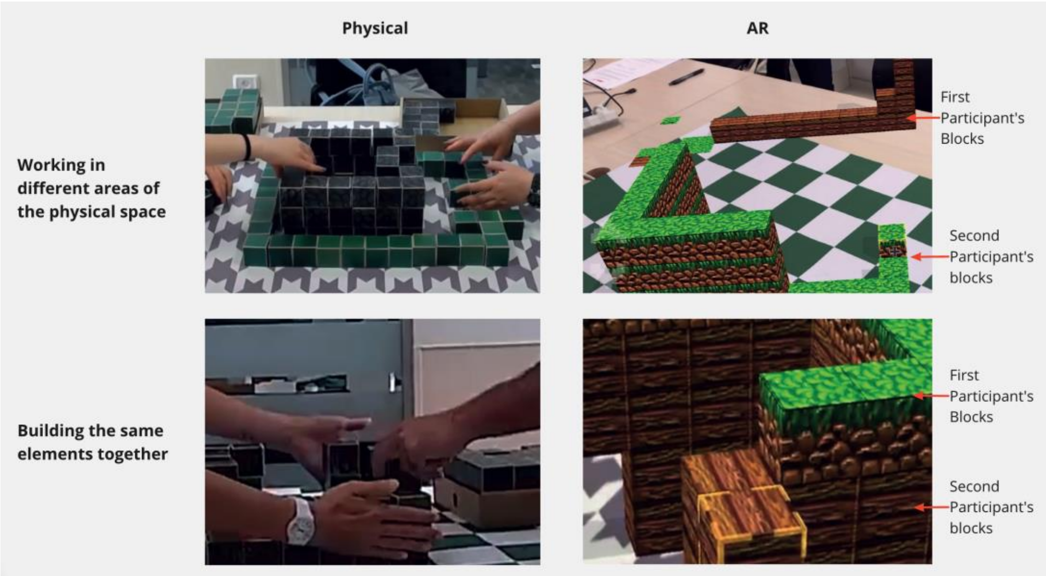

Figure 4: Illustration of area-based and element-based task allocation behaviors in the Physical and the AR conditions.

In addition, we compared the time spent in different styles of task allocation within each experimental condition. The analysis indicated that the differences between these two task allocation modes were not significant in the Physical condition indicating the relatively even distribution of time spent by the participants in each task allocation mode in the Physical condition ($t=1.31$, $p=0.20$). In contrast, the difference between the different task allocation modes in the MAR condition was significant ($t=7.09$, $p<0.001$), with much more time spent in the area-based task allocation. This finding demonstrates that the participants mostly preferred to work on different parts of the structure in the MAR condition.

4.1.2 Movement Around the Physical Space

During our observations, we noticed that the utilization of the physical space played an important part in structuring and informing the participants' coordination behaviors during the experiment. The participants often moved from place to place around the table, and these movements served as communication and coordination signals. For example, the participants sometimes moved to another part of the table to signal to their partner that they have finished working on the previous element of the structure. We also observed how the participants moved to their partner's side to understand their visual perspective on the building (e.g., how does the building look from their position).

We identified several modes of coordination based on the extent to which the participants utilized the shared physical space during their work, namely, how much they moved around the space while working and what positions they took relative to each other:

1. *Movement dynamics:* refers to the extent to which the participants actively moved around the workplace during the work process. We operationalized this behavior by counting the number of times participants moved from one stable position to another during the co-design process (by moving their feet). Each substantial change in a physical position that resulted in the participant going from one stable location to another was counted as one movement event.
2. *Formation choice*: referring to how the participants chose to position themselves in relation to their partner. We observed three forms of formation choices (see Figure 5):
3. 0 degrees (*Near*), where the participants chose to stand or sit near each other, at the same side of the table,
4. 90 degrees (*Adjacent*), where the participants chose to stand or sit on adjacent sides of the table, making a 90-degree arc between them,
5. 180 degrees (*Opposing*), where the participants chose to stand or sit one in front of the other, on opposite sides of the table.

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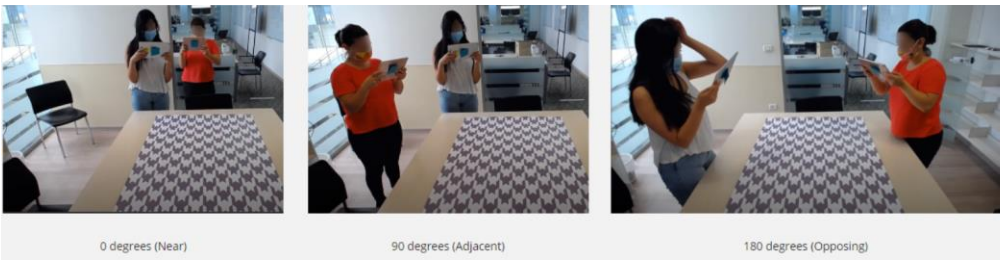


Figure 5: Demonstration of different formations of the participants' during the experiment

Movement dynamics. We counted the number of times the participants changed their physical position around the table (by moving their feet). Each substantial change in a physical position that resulted in the participant going from one stable location to another was counted as one movement event. We found a large difference in position changing instances between the MAR and the Physical conditions. The average frequency of changing position per session in the MAR condition was 24.47 times vs. only 5.5 times in the Physical condition. The difference was statistically significant ($t=9.62$, $p=0.001$).

The increase in participants' movement was very noticeable when observing the participants in the MAR condition. In the Physical condition, when deciding to work on the farther sides of the artifacts, the participants often reached the other side with their hands and retained their static position at the table. In the MAR condition, the participants increasingly preferred to move to entirely new positions instead. In principle, it was entirely possible to move the device around to look at the structure from above, below, or from different sides. However, we noticed the general reluctance of the participants to move their hands to hold the tablet at a different angle. Instead, they moved their whole body to change where they look, which contributed to the overall increase in movements in the MAR condition.

Formation choice. In the Physical condition, the participants spent on average 163 seconds per task in the Opposing formation, 149 seconds in the Adjacent formation, and 41 seconds in the Near formation. In the AR condition, the participants spent on average 101 seconds per task in the Opposing formation, 166 seconds in the Adjacent formation, and 143 seconds in the Near formation.

The statistical analysis indicates a significant difference between the participants spending time in the Near formation in the Physical vs. the MAR conditions, demonstrating that in the MAR condition, the participants worked closer to each other compared to the Physical condition ($t=2.69$, $p<0.0.3$). In addition, the difference between the time spent in the Opposing formation between the Physical vs. MAR conditions was also significant ($t=3.09$, $p=0.007$). The average time spent by the participants in each formation in both experimental conditions is summarized in Figure 6.

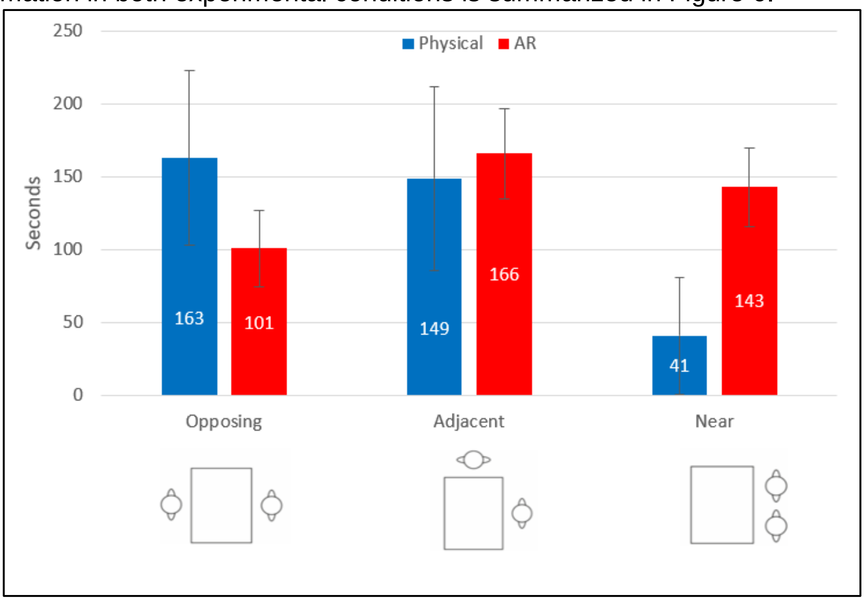


Figure 6: The average time in seconds spent by the participants in each formation in the AR and the Physical conditions

Working close to each other in MAR was necessitated by an increased need of the participants to understand each other's perspectives on the artifact of work. Because they lacked a constant shared physical reference (e.g., the structure itself), the collaborators could not easily understand how the artifact looked from the perspective of their partner. Thus, they moved close to each other to see the artifact from a similar angle and direction of view. Moreover, we noticed how in several instances, the participants quickly glanced at their partner's device's screen to even better understand what exactly their partners were doing at the moment.

Our finding of the participants working closer to each other in the MAR condition is somewhat counterintuitive given that on the whole, while working in AR, they moved around much more. However, when we observed the overall patterns of the space utilization in the AR condition, we saw that the participants utilized a more diverse range of spatial positions for shorter periods of time. They moved back and forth quite a lot, often briefly coming together and then adopting other positions around the table.

4.1.3 Deictic Referencing Towards the Artifact/Structure

Deictic referencing towards the artifact/structure describes bodily gestures (e.g., hands, head, torso), referencing the particular parts of the structure while building, with a goal to direct the attention of another participant to the particular element in the co-designed artifact. Additionally, we counted as deictic the gestures that were used to symbolically describe and show one's partner the general form of the intended structure or its elements. For example, we observed how the participants made a contour of the elements of the structure in the air by waving their hands to describe this element's intended geometry to their partners. Moreover, they often defined the borders of the future structure by delineating the space on the table with their hands, pointing to specific places or parts of the structure when discussing it together, and waiving in the general direction of the building's parts to indicate to the collaborator where they intended to move. While in most cases, deictic referencing took the form of hand gesturing, sometimes the participants used their heads to indicate the general direction in which they wanted to focus the attention of their partners.

A rich deictic behavior in the physical condition contrasted with a mostly verbal character of referencing in the MAR condition. Namely, while working in MAR, the participants often narrated their actions to keep their partners in the loop. Also, they referred to different parts of the artifact by verbally describing its location, form, or function (e.g., "*look to your left, this square thingy that [hangs from] the column*").

On average, the participants performed 10.5 hand gestures per session in the Physical condition compared to 2.2 in the MAR. The difference between the conditions was significant ($t=3.25$, $p<0.01$), indicating that the participants mostly avoided deictic referencing when working in the MAR condition.

4.2 Assessing the Participants' Subjective Perceptions and Experience

Overall, the participants assessed their subjective experience of their work in the MAR and the Physical conditions fairly similar. Namely, the majority of the participants explained that they see the MAR condition as a variation or extension of the Physical condition and that it feels similar while providing the extended capabilities. The only significant difference in the participants' ratings was observed in their perceptions of the quality of collaboration during the task. The participants rated the quality of collaboration as being higher in the MAR condition (average rating of 4.5) compared to the Physical condition (average of 4.2). The difference was statistically significant ($Z=-2.42$, $p<0.016$), indicating that the perceived collaboration was better in the MAR condition. Table 1 presents participants' average scores of their subjective perceptions in both experimental conditions.

Table 1: the participants' perception of *collaboration*, user experience, creativity of work and quality of work in each experimental condition on the scale from 1 to 5, N=46

Scale	Scores	
	Physical	AR
Collaboration	4.2 (0.8)	4.5 (0.6)
User experience	4.3 (0.6)	4.3 (0.6)
Creativity of work	3.6 (0.8)	3.8 (0.8)
Quality of output	3.7 (0.8)	3.8 (0.7)

When asking participants to directly compare the two conditions, some interesting patterns emerged. As can be seen in Table 2, most of the participants stated that the Physical condition was easier to use than the MAR condition. However, despite the easiness of the Physical condition, most of the participants thought that the MAR mode was the more creative. The same trend persisted with regards to effectiveness and fun - most participants thought that the MAR condition was more effective and fun to use than the Physical condition.

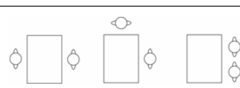
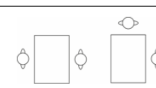
Table 2: the participants' direct comparison choices of subjective experiences when comparing both experimental conditions.

Metric	Participants' Preferences (percentage)	
	Physical	AR
Easy	72%	28%
Creative	28%	72%
Effective	35%	65%
Fun	20%	80%

4.3 Summary of the Results

We observed several key differences in the participants' coordination-related behaviors in the Physical and the MAR experimental conditions. In the Physical condition, the participants spent most of their time building the parts of the structures together, while in the MAR condition, they mostly divided the tasks by physical areas and, instead of working on the different parts of the same structural element, worked on different elements located in the corresponding areas. Consequently, the participants' moved around the workspace much more in the MAR condition, utilizing the available physical workspace in their coordination activities. Moreover, in the MAR condition, the participants exhibited much more diverse formation choices than in the Physical condition, almost evenly distributed between being opposed, adjacent or next to each other. Conversely, in the Physical condition, the participants were mostly opposed or adjacent to each other while avoiding working next to each other. Finally, we observed significant differences in the amount of deictic referencing used by the participants to coordinate and guide each other's activities. In the Physical condition, the participants exercised much more deictic references than in the MAR condition, actively referencing the structure and its elements. Table 3 summarizes the identified coordination-related behaviors, including the results of the statistical analysis of the differences in the observed metrics between each experimental condition.

Table 3: Summary of the differences in coordination behaviors between the AR and Physical experimental conditions

	AR	Physical
Task Allocation	The same functional element	Different areas in the workplace
Formation		
Number of movements	High	Low
Number of deictic gestures	Low	High

5 DISCUSSION

We compared coordination behaviors of dyads of participants in a collocated collaboration task around 3D artifacts in fully physical vs. augmented reality conditions. We found that these two conditions produced different coordination styles that we can broadly term as:

1. ***Space-oriented coordination***, characterized by allocating the tasks according to the different areas in the workspace, making few deictic references referencing the work artifact, and actively moving and changing positions around the workspace; this coordination pattern was most salient in the MAR experimental condition.
2. ***Artifact-oriented coordination***, characterized by allocating the tasks around the same elements of the work artifact, building these elements together, making many

deictic gestures referencing the work artifact, and more static positioning around the workspace; this coordination pattern was most salient in the Physical experimental condition.

Our findings suggest that 'physicality' serves as an anchor for coordination, highlighting the importance of the shared physical dimension for facilitating collocated collaboration. In the Physical condition, the existence of the shared physical artifact allowed the participants to use it as an anchor for their coordination needs. In the MAR condition, in the absence of a physical artifact to coordinate around, the participants used the shared (physical) workspace as a locus for their coordination. Interestingly, participants perceived the conditions as equally effective for collocated collaboration. We conjecture that the variations in coordination patterns between the MAR and Physical conditions stem from the ways in which the physicality of the artifact (in the physical condition) and space (in both environments) afford mutual awareness of each other's explicit and intended actions. In the following sections, we further discuss our findings, link them to the extant knowledge in the field, and highlight our study's novelty and contributions.

5.1 The Effect of Mutual Awareness on Coordination Behaviors

We believe that the primary reason for the difference in coordination behaviors observed between the MAR and the Physical conditions is the limitations that the MAR technology places on participants' mutual awareness: the ability to understand each other's up-to-moment interactions and intentions in a shared workspace [32, 33].

In the Physical condition, the participants could easily adjust to each other's actions and predict each other's intentions. This richness of available communication cues provided effective support of *exocentric awareness* – the awareness of others' actions and intentions [4, 86]. As described in the findings, the participants could understand precisely what their partner was pointing at, where was she focusing her attention, and where was she placing or intending to place the block by implicitly observing her hand movements, gaze direction and general actions. Overall, we observed how the increased mutual awareness enabled participants to use artifact-oriented coordination: allocating tasks focusing on the same elements of the artifact, incorporating turn-taking and deictic gesturing, thus complementing each other's activities while not interfering with each other's work.

Contrastingly, while the MAR condition supported *egocentric awareness* (i.e., understanding one's own position in space relative to the other individuals and the design artifact), it decreased the exocentric awareness. Gaze tracking may have been increasingly hard, and deictic gestures were meaningless, as both collaborators lacked a precise shared physical point of reference in space. Moreover, the participants mostly focused on each own's device, which decreased opportunities for implicit tracking of other's actions. This focus on one's own device likely served as a means to avoid the high cognitive costs of switching between the device and the partner. Indeed, Wells and Houben found that participants in a collocated MAR setting performed a large number of context switches between looking at the device and face-to-face communication [100]. The increased need for divided attention resulted in a high mental and cognitive load and decreased the quality and amount of collaboration [100].

In our experiment, the participants evidently preferred to avoid increasing cognitive load at the expense of maintaining face-to-face communication. While this changed the overall patterns of coordination, we did not find evidence of declined overall performance during the experimental task. In addition, the participants indicated that they were equally satisfied with the results of their work in both conditions and even pointed at the MAR condition as better supporting their creativity. This finding may be consistent with a previous study by Prytz and colleagues [73] that found that a decrease in opportunities for eye contact during AR collaboration did not directly influence teamwork in negative ways.

Finally, in the MAR condition, participants manipulated the blocks by aiming on their device at the place where they intended to place them (or aiming at other blocks they wish to interact with) and did not physically reach their hands in an attempt to place or remove the blocks. This also reduced the exocentric awareness, as tracking one's hands was no longer useful. In such a case, artifact-oriented coordination was likely perceived as a suboptimal choice, and the participants preferred to work on different parts of the structure, adopting a space-oriented coordination style.

The decreased support for mutual awareness in MAR can also explain why participants in our study were moving more as well as working in more diverse formations in this condition, often positioning themselves at the same side of the table (while still building in different zones). Looking at the design artifact from the same perspective helped the participants to establish a shared understanding of the artifact and better understand their partner. Once a shared understanding had been achieved, the participants continued moving around to different areas.

Previous works in CSCW and human factors emphasized the critical role that mutual awareness plays in the success of the collaboration [1, 32]. The role of mutual awareness is known to influence user collaboration in groupware systems and tabletop environments [19, 32, 51, 92], as well as in remote AR collaboration [9, 10, 52, 70].

Various techniques had been proposed to enhance mutual awareness (e.g. [51, 70]), focusing on increasing the sense of embodiment [40, 69, 70] and visualization of implicit cues [45, 84]. The novelty of our findings is in demonstration that even when the MAR users are physically collocated and thus have an increased ability to communicate compared to a remote collaboration scenario, the MAR setting still produces variations in the coordination behaviors, changing the patterns of coordination compared to a fully physical setting. However, our participants were able to compensate for the lack of exocentric awareness by leveraging the shared physical workspace to allocate tasks in separate areas of the workspace, supporting their coordination by movement, and adopting diverse formations relative to each other.

We can connect our findings to the behavioral framework of collaborative coupling in computer-mediated environments. Collaborative coupling in the context of HCI and

CSCW refers to the "manner in which collaborators are involved and occupied with each other's work" during collaborative activities [32, 51]. Using Tang and colleagues' taxonomy [93], we can describe the work in the Physical condition in a manner of the same problem, same area, where the participants were actively involved in each other's work, building and evaluating the elements of the structure together. Such a manner of work is typically associated with tight collaborative coupling [93]. The work in the MAR condition can be described as tight-to-medium coupling style [93], in a manner of the same problem, different area collaboration.

5.2 Object-Manipulation Techniques as a Physical Constraint

Beyond serving as a mutual awareness mechanism, the differences in how the users manipulated the artifacts in the MAR vs. the Physical condition bounded the coordination behaviors of the participants by establishing what is physically possible to do. *Reaching with their hands to manipulate the artifact* afforded by the Physical condition allowed more flexible interactions with the work artifact, where the participants could mostly reach every side of the design artifact from different angles without moving to another place, decreasing the need to move around the workplace. Even when the part of the artifact was obstructed by other elements of the artifact from a particular position, the participants could still reach it by arching their hand over the obstructing element.

In contrast, the *aim-based object manipulation* in the MAR condition was fully dependent on a direct line of sight. Namely, the participants could put the blocks in the particular place only if they could directly aim there. Such an aim-based object manipulation technique is a highly common and acceptable way to implement interactions in MAR [86]. In our experiment, this way of interaction made it considerably harder to put blocks on the farther sides of the building if the elements on the closer side obstructed the clear line of sight, or under sharp angles, necessitating the user to move to another location.

Previous works on collocated collaboration in mixed environments had explored a variety of interaction techniques to enable collaborative work, such as gestures [67, 68, 74], external controllers [39, 79], touch interactions [31], and tangible objects [35]. However, the majority of the existing input modalities still use the aiming technique as the basis of indicating the point or element of interest to the system [63, 69], particularly in the context of mobile AR. We show how this basic interaction approach affects the coordination behaviors of collaborators in a shared MAR environment. In particular, we demonstrate that the aiming technique may encourage space-based coordination by limiting the parts of the artifacts that could be reached from a particular position.

5.3 Users' perceptions and experience

In both the MAR and the Physical conditions, the participants enjoyed the activity and rated their collaborative experience as very high. Perhaps surprisingly, the perceived quality of collaboration in the MAR condition was even higher than in the Physical condition. It could be argued that the user experience may have been affected by the novelty effect of AR. However, during the interviews, the participants had pointed out that they had perceived the experimental conditions to be very similar, essentially viewing the MAR condition as a "modified" version of the Physical condition. Evidently, the ability to leverage the physical workspace for coordination led to similar perceptions of both conditions, even if some coordination adjustments were required.

Previous studies on user perceptions of AR highlighted the importance of physical background for perception of virtual objects. Specifically, it was found that virtual objects in MAR are experienced as being more real or genuine than the same objects viewed in the fully virtual settings [71, 72]. We extend the previous findings by demonstrating that the collocated collaborative MAR setting is viewed as being similar to the fully physical setup. Our finding somewhat contradicts the previous studies on collocated AR collaboration that found that MAR may negatively affect the user experience, reduce user comfort, and lead to a decrease in performance [54, 99, 100]. This discrepancy may be explained by the nature of the experiment and the tasks performed by the participants. For example, in [54], the participants played an AR table game while seated opposite each other and were not allowed to move around the table. Thus, the crucial aspect of physical space was not utilized in this particular setup. In [100], the participants had inspected highly complex 3D models via a small smartphone-based AR system. This small form factor could explain the increased cognitive effort of the participants.

Comparing the user experience in our study with the results of the studies above leads us to emphasize the necessity of an individual approach to the deployment of MAR technology for collaborative tasks. Plainly, there is no one-size-fits-all technical MAR solution for each and every collaborative task. Our findings imply that the benefits of MAR for design collaboration are in leveraging the properties of digital artifacts while still being able to coordinate around shared physical dimension. These properties make MAR particularly fit for the prototyping stages of product design, where the ability to quickly change the artifact is as important as the ability to build collaboratively.

6 LIMITATIONS AND FUTURE RESEARCH

An important limitation of the current work stems from our choice to use mobile AR technology. Arguably, this choice may limit the generalizability of this work, as other forms of AR (such as a headset or projection-based AR) may have different affordances and have their own idiosyncratic limitations. We chose to focus on MAR due its widespread use and accessibility. We show that even in the constrained form of mobile AR, the physicality of the space provides the participants enough affordances to successfully collaborate. However, with the gradual increase in the availability of AR headsets, future researchers need to also examine the use of HMD-based AR for collocated work.

Our study was done in the particular context of collocated collaboration around the design of 3D artifacts. Previous studies had shown that AR technology is not a universal solution for every kind of computer-mediated collaboration, often requiring an individual approach. Future studies should map this space to create a design and implementation framework for advancing AR for a wide range of collaborative use cases.

Particularly, more research is required on how to support mutual awareness and transition between coordination modes in collocated AR. Our findings show that the decrease in mutual awareness in MAR can reduce the ability of the users to work in tight coupling mode. However, in most real cases, collocated collaboration requires the users to fluidly transition between different modes of work, switching from tight to weak coupling and back [93], depending on the current stage and state of the work. For example, one of the most popular M]AR techniques to improve user awareness is ray casting (e.g., indicating the precise position of what the user is pointing at by casting a visible ray from the pointing device to the surface point in the physical environment) [37, 79, 80]. Future research can look at multiuser ray casting as a technique to enhance mutual awareness of the participants in collocated collaborative headset and mobile-based AR.

In our study, we mostly focused on the non-verbal behavior of the participants, such as deictic referencing and consequential communication in the form of movement, working formations, and task allocation. However, verbal communication is an indispensable form of information exchange that is crucial for the success of collaborative tasks. Thus, it is imperative to investigate verbal communication in future research on AR collaboration and coordination. Previous studies had shown how the interaction of non-verbal and verbal communication may affect collaborative actions [46]. Particularly interesting in this regard is the study of deictic linguistic expressions that complement gestures for efficient referencing.

Our setting involved collaboration between the two collocated participants. However, the collaboration dynamics can change drastically when more than two participants are working together. Future studies would examine collocated collaboration in MAR with larger groups of collaborators. Also, it is interesting to take a closer look at the end-product of the collaboration. While we asked participants to rate the quality of the collaboration and the quality of the resulted structure, it may be possible to take a more objective look, examining how the use of AR may affect the outcome of the design artifact. For example, it could be that the buildings that the users create in MAR are structurally and stylistically different from those built in the Physical condition, or participants might use fewer materials or build higher towers in one or other condition.

Last but not least, while much of current focus of the research community is on exploring remote and collocated AR environments, less is known about users' collaborative needs and behaviors in hybrid settings, where some of the participants are collocated, and others may participate remotely. The need to enable hybrid collaborative environments is being increasingly recognized [58, 101]. However, most of the work in this direction had been performed in the fields of groupware and robotic telepresence (e.g., [44, 83]. Initial studies started exploring how remote and collocated users can collaborate in mixed AR-VR settings [96]. We believe that this is an exciting direction for future research.

To conclude, our work shows the potential of shared MAR as a technological platform supporting collocated collaboration around the design of 3D artifacts. We show how the use of MAR affected the coordination behaviors of users, without affecting their experience or perceived work outcome. We hope that our findings will contribute to the scholarly effort of research on user interactions and communications in shared AR and MAR and inform practitioners who will drive this technology further, creating ever-better collaborative environments.

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