Brick: Toward A Model for Designing Synchronous Colocated Augmented Reality Games

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ABSTRACT

Augmented reality (AR) games have been growing in popularity in recent years. However, current AR games offer limited opportunities for a synchronous multiplayer experience. This paper introduces a model for designing AR experiences in which players inhabit a shared, real-time augmented environment and can engage in synchronous and collaborative interactions with other players. We explored the development of this model through the creation of *Brick*, a two-player mobile AR game at the room scale. We refined *Brick* over multiple rounds of iteration, and we used our playtests to investigate a range of issues involved in designing shared-world AR games. Our findings suggest that there are five major categories of interactions in a shared-world AR system: single-player, intrapersonal, multiplayer, interpersonal, and environmental. We believe that this model can support the development of collaborative AR games and new forms of social gameplay.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; • **Applied computing** → *Computer games*;

KEYWORDS

augmented reality, synchronous, colocated, collaborative

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1 INTRODUCTION

Mobile augmented reality (AR) games place interactable digital game objects in the players' physical surroundings, typically using the phone camera. These games can encourage players to attend both to game objects, and to how those objects are placed in the physical environment. However, the games currently available offer limited opportunities for multiplayer experience in AR. At present, *multiplayer AR* games typically reduce to single-player experiences that may or may not encourage players to be in the same physical location, with an asynchronous communication capability across multiple devices. For example, the game *Pokémon Go* has "gyms" in which players are able to battle each other via individual, asynchronous interactions on their own devices [24, 26]. As of this paper's publication, unpublished work by Facebook extends the concept of multiplayer AR games to include remote, synchronous experiences mediated through Facebook Messenger [1].

Taken together, these developments suggest the potential of AR games to connect people not just with their own physical environments but also with each other. In order to realize this future, the concept of multiplayer AR must be extended to include *shared-world AR*, in which players inhabit a shared, real-time augmented environment and can engage in synchronous and collaborative interactions with other players.

Shared-world AR game design is a largely unexplored space at present. Few shared-world AR games currently exist; current exemplars, such as *LightBoard* [13] and *SwiftShot* [3], are competitive experiences restricted to the tabletop. There

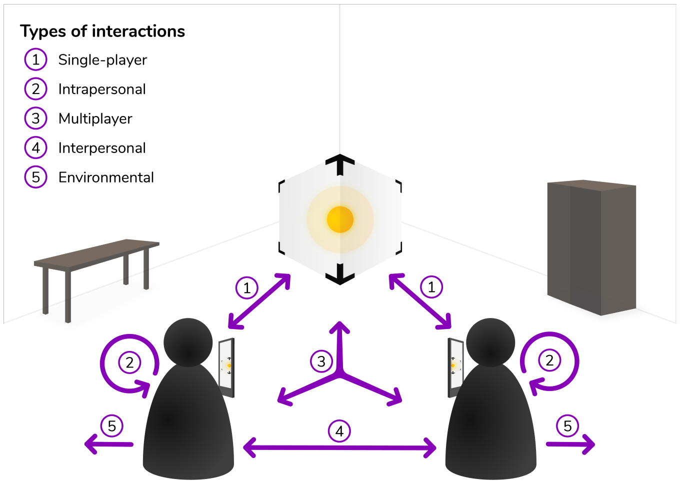

Figure 1: A diagram showing the five main categories of interactions in a two-player shared-world AR environment. ©Po Bhattacharyya

is some preliminary work into establishing guidelines and heuristics for AR games on mobile [4], but an equivalent design guide for shared-world AR does not currently exist. Consequently, there is a need to establish best practices for designing shared-world AR experiences and building systems to support their development.

In this paper, we describe a shared-world mobile AR game, *Brick*, in which players engage in synchronous interactions at the room scale. We developed *Brick* as a two-player game using Google's ARCore technology, which allows networked mobile devices to access a synchronous and interactive AR environment. We playtested *Brick* across multiple iterations and developed design principles for a number of individual and collaborative interactions for shared-world AR on mobile phones. For a two-player shared-world AR system, we identified five categories of interactions: single-player interactions, which play out between individual users and the AR interface; intrapersonal interactions, which involve an individual user's internal deliberations and experiences; multiplayer interactions, which play out between multiple users and the AR interface; interpersonal interactions, which involve multiple users but not the interface; and environmental interactions, which involve users and their physical environment (see Figure 1). Our findings suggest that opportunities for game design decisions exist at the intersection of individual players, the mobile AR interface, and the physical environment. As such, in a shared-world AR system, even individual interactions with the AR interface have interpersonal and environmental implications.

2 BACKGROUND

The concept of AR gaming entered the mainstream in 2016, with the launch of *Pokémon Go*, but AR games have been around for much longer. One early example is *Eduventure*, an educational game based on a quest, which came out in 2005 [10]. In a 2008 paper on AR games, Broll et al. [5] identified two early trends in the field: small-scale individual games, and large-scale event-driven games that are linked to locations in the physical environment. AR gaming has since grown to include a wealth of games for handheld devices, head-mounted displays, as well as wearables [6, 15, 17, 29, 31]. The handheld device is by far the most democratized platform for access to AR. In a 2018 review, Laine [15] observes that "head-mounted displays have increasingly given way to powerful mobile devices equipped with cameras that can create mobile AR experiences in a context-aware manner."

There has lately been an explosion of multiplayer AR games for mobile. These games fall into two broad categories: asynchronous and synchronous. The key difference between these two categories is whether players can act at the same time (synchronous) or if they take turns (asynchronous) [9]. Recent examples of asynchronous games include *Ingress* [22], *Run an Empire* [27], and *Pokémon Go* [23]. As of this paper's publication, these games are location-based and have limited multiplayer functionalities in AR. Each of these games might be more accurately described as a collection of colocated single-player experiences. In our view, they cannot be considered shared-world AR experiences.

Our survey of the existing landscape yielded two AR games with synchronous-AR capabilities—*SwiftShot* [3] and *LightBoard* [13], which are the demo games for Apple's ARKit and Google's ARCore respectively. These games do an excellent job of showcasing the technological capabilities of their respective software development kits (SDKs), especially as they relate to the creation of shared-world AR experiences. However, these games do not contribute much toward our understanding of the design principles underlying shared-world AR. In both games, play is restricted to the tabletop and players are largely rooted in position, so the opportunities for designing environmental interactions are limited. We studied these games during our design process, and chose to focus on synchronous colocated play in AR because there were relatively few design exemplars in this space. In this project, we were particularly interested in exploring the challenges of designing for the room-scale embodied interactions that players are likely to expect to be able to perform in AR [31].

While AR technologies have been around for many decades, researchers have only recently begun to focus on studying usability considerations and design principles underlying AR interfaces [7]. Both Apple and Google have useful design guides for mobile AR; both guides make generalized recommendations about designing for variable environments, for movement and user safety, for the realism of augmented objects, for improving discoverability, and for improving error recognition and recovery [2, 12]. In the realm of mobile AR games, Lee and Lee (2016) established a heuristic evaluation framework that takes three different factors into consideration: presence, i.e., the degree to which a user feels grounded in their physical reality; affordance, i.e., the ease with which a user perceives the purpose of an object or interaction; and usability, i.e., the efficiency and satisfaction with which a user is able to accomplish their goals on the platform [16].

Similar to traditional mobile AR, shared-world AR involves design considerations around player movement, which draws from the literature on designing for movement-based game experiences. Mueller and Isbister (2014) state that "movement-based games align with a larger trend in HCI around embodied interactions that put the body in the center of the interactive experience." Their work has established a number of useful guidelines for movement-based game design: embracing the ambiguity (i.e., lack of positional precision) that comes with room-scale movement; providing rewards for well-executed movements; offering multimodal feedback that does not involve the screen; and designing for environmental awareness (i.e., the opposite of immersion) [20].

Additionally, designing for shared-world AR involves the consideration of inter-player communication and proximity. Games have been used to explore bodily interactions between people, especially those interactions that involve awkwardness and touch [11, 14, 18]. Touch-based, or haptic, feedback has been used to encourage intimacy [8]. Recent work has also investigated the outcomes of gentle touching between the body parts of two players; their recommendations include encouraging ways to create bodily awareness of others (opposite of designing for immersion), encouraging interesting and expressing touch (e.g. need a high-five to start the game), and allow opportunities for *expressive latitude*, i.e., opportunities for players to express themselves in ways not sensed by the interface [19].

3 METHODS

We created a synchronous, collaborative, room-scale game to explore the design principles underlying shared-world AR experiences. We employed the tandem transformational game design process to create this game; tandem design is an iterative process that alternates between research and design throughout the development process [28].

Game Design and Development

Brick is a collaborative game in which two players work together to fill in a pattern of empty slots in a grid, using AR bricks that are scattered all over the room. Some of the

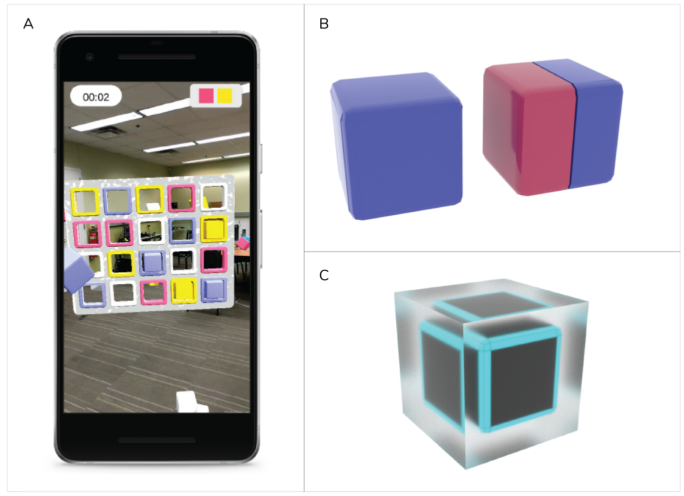

Figure 2: A diagram showing the major augmented objects that appear in *Brick*–a pattern of empty slots as seen through a mobile device (A), individual and collaborative bricks (B), and the bomb (C). ©Ketki Jadhav

bricks need to be collected individually, while others must be collected by both players working together. To win, the players must fill in the entire pattern before time runs out. At some point during the game, a bomb appears in the pattern, and the bomb must be defused collaboratively within seven seconds. If the bomb isn't defused in time, it sets the players back by knocking off adjacent bricks in the pattern.

The augmented objects in *Brick* include the pattern of empty slots, individual bricks, collaborative bricks, and the bomb (see Figure 2). The bricks come in four colors, and each player can interact with two of those colors. Each individual brick has one color; each collaborative brick has two colors, one from each player. Players can collect and transport bricks using a tap-and-hold interaction in AR. The bomb is a visually distinct piece that appears during gameplay.

Brick is a synchronous game. Both players are actively collecting bricks throughout a session of gameplay; they do not take turns. The networking in the game is able to update game state in real time so that players can keep track of their own progress as well as that of their partner.

Brick is also a collaborative game. The players must work together to win the game, and this involves active communication as well as coordinated movement at close quarters. For example, the collaborative bricks must be picked up and carried by both players simultaneously. Players must also work together to defuse the bomb when it appears in the pattern.

Brick was developed iteratively, based on insights from multiple rounds of playtests (see 3.2). Our original goal was

Table 1: Brief descriptions of early prototypes

Name	Description
Ice-cream Truck	Assemble sundaes with your partner in an ice-cream truck, and keep robbers at bay.
Space Between Us	Work with your copilot to reassemble your spaceship after crash-landing on an alien planet.
Treasure House	Collect clues in household objects and follow their trail to find the hidden treasure.
Coffee Farmer	Collaborate with your partner to grow the best coffee in the land, in your own house.
Lab Rat	Join forces with wild rats to wreck science experiments and secure your freedom.
Squirrel & Nut	Collaborate with your squirrel mate to collect nuts, against all odds.
Landmine	Work together to make your way across fields covered in hidden landmines and other dangers.
Gift of the Magi	Work with your partner to anticipate and solve each other's problems. No talking aloud!

to create a mobile-AR game that encourages communication, laughter, and movement. During our design process, we used the round robin brainstorming technique [21] to design nine different games (see Table 1 for brief summaries of each, and the Supplementary Materials section for extended descriptions), and we conducted internal low-fidelity playtests to narrow the list down to one. During our internal playtests, we scored each game against a rubric based on our original design goals and on the technological constraints of mobile AR. After several rounds of team discussion, as well as feedback from expert game designers who scored our games using the same rubric, we arrived at a consensus with Brick. We prototyped *Brick* in low-fidelity by using Post It notes mounted on a wall, and moved through iterations of successively higher fidelity. Our final prototype was a two-player game in augmented reality that included individual bricks, collaborative bricks, as well as a bomb. High-fidelity prototypes of the game were developed on the Unity game engine using Google's ARCore SDK.

Playtesting

We playtested *Brick* with 14 participants across low- and high-fidelity iterations of the game. These participants were recruited via an online survey distributed widely through email listservs, Facebook, and Slack. All the participants were in their 20's and 30's, but they came with a wide range of prior experience with augmented reality.

Playtest sessions took place on the Carnegie Mellon University campus and lasted between 30 minutes and 1 hour. We collected audio and video footage of the each playtest. Each session included a short introductory conversation, then multiple rounds of gameplay, and finally an interview about the gameplay experience. The introductory conversation inquired into participants' prior experience with AR and, for two-player playtests, the players' relationship with each other. Gameplay began with a short description of the rules, followed by multiple rounds of the game. The post-game interview was an extended conversation with four sections: general gameplay, inter-player dynamics during the game, main takeaways from the game, and an exit debrief. The questions in the post-game interview were adapted in part from prior work at Schell Games [25].

Shared-world AR Model Development

We used *Brick*'s iterative design and development to study a number of interactions that are integral to the game. Early on, we created an exhaustive list of Brick's in-game interactions. This list included observable interactions, such as picking up and dropping off augmented objects, and abstract interactions, such as players' internal thoughts during gameplay. Then, we identified quotes from our playtests that referred to in-game interactions. We coded the quotes using an iterative process, coming to consensus among team members about codes between each round of iteration.

Our shared-world AR model was derived from our iterative coding process, and relationships between model elements represent overlaps in codes. For example, quotes coded as both "multi-player" and "interpersonal" showed us the relationship between those elements. (See the Supplementary Materials for representative excerpts from our coded data.) Once there was consensus among all the researchers, we sought feedback from game design experts to make sure that our model captured all aspects of gameplay in *Brick*. Finally, we used *Brick*'s playtests to focus on selected interactions from each category in our shared-world AR model.

4 RESULTS AND DISCUSSION

We have identified five major categories of interactions in a shared-world AR system. As shown in Figure 1, they are single-player, intrapersonal, multiplayer, interpersonal, and environmental interactions. In this section we offer examples

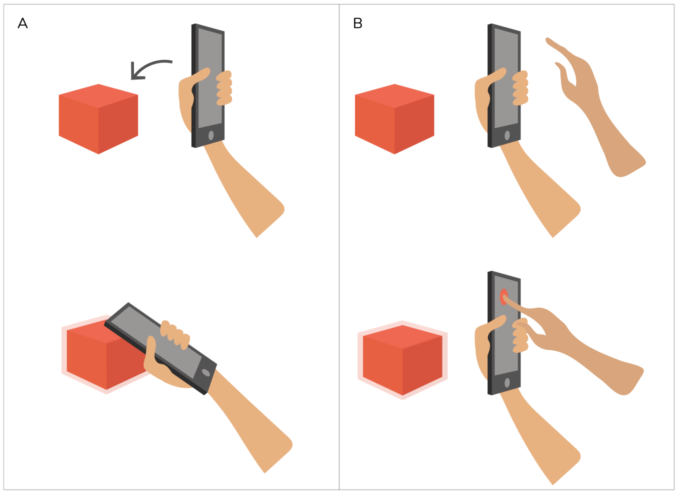

Figure 3: A diagram showing the two major pick-up interactions we playtested during *Brick*–(A) slam and (B) tap-and-hold. ©Po Bhattacharyya

Table 2: Comparison of Slam and Tap-and-hold Interactions

Slam Interaction	Tap-and-hold Interaction
Gross-motor interaction–requires an involved, sweeping movement of the wrist and forearm	Fine-motor interaction–requires a small, precise movement of a single finger only
Momentary interaction–an initial slam is all that is needed to hold on to brick	Continuous interaction–finger needs to be pressed down to hold on to brick
Uncommon–there are few examples of slam motions in other applications	Common–this is a standard interaction for mobile phones
Conspicuous–one player's actions are easily visible to the other player.	Inconspicuous–one player's actions are not visible to the other player.
There isn't a clear affordance for how to drop off a piece.	There is a clear affordance for how to drop off a piece (lift finger).

of each category of interaction, representative quotes from our playtests, as well as a discussion of how we explored these interactions in our iterative design process.

Single-player Interactions

> "I don't understand why I can't interact with smaller blocks that are farther away."

These are interactions between a single player and an augmented object, such as a brick. During gameplay, players collect bricks from around the room and carry them to appropriate slots on the pattern. This involves three principal interactions–pick up, carry, and drop off.

In designing single-player interactions, building on familiar metaphors for interacting with the mobile phone turned out to be important. We prototyped two gesture-based controls in AR: first, a slam interaction, in which players pick up augmented bricks by slamming them with with their phone (see Figure 3A); and second, a tap-and-hold interaction, in which players tap and hold down their finger on the brick as seen on their phone (Figure 3B). During our playtests, we found that players preferred the tap-and-hold interaction over the slam interaction for picking up bricks. A common issue raised by players was discoverability. The slam interaction was a relatively novel interaction that wasn't accompanied by sufficient affordance, i.e., players had no way of knowing that a slam was required to pick up a brick, other than the pre-game explanation. We observed that players found the slam interaction unintuitive and cumbersome. The tap-and-hold interaction, on the other hand, is a much more prevalent interaction for touchscreen interfaces, and it came to players more naturally. A number of playtesters told us that their first instinct would be to pick up bricks by tapping on the screen of the phone. So we decided move ahead with the tap-and-hold interaction. The results from our playtests of the two interactions are summarized are in Table 2.

Notwithstanding the intuitive nature of the tap-and-hold interaction, it became a problem in two cases. First, the AR interface did not clearly indicate the distance of an augmented object from the player. During our playtests, we noticed that some players struggled to pick up bricks because they didn't realize that the bricks were too far away to pick up. So, we decided to add a hover state as visual feedforward to players: individual bricks assigned to a player respond to that player's proximity by assuming a translucent, pulsing glow. We argue that a conspicuous hover state is a definitive way to indicate both size and proximity of an augmented object to the player; it's an easy way to indicate that a player is close enough to the object to be able to interact with it.

Second, the AR interface didn't offer a clear feedforward about how to carry an object once it is picked up. During our playtests, we noticed that players didn't realize that they had to press down with their finger to hold on to the brick. So, we decided to add more scaffolding to support state awareness. In the current iteration of the game, a brick alters its position to align with the phone's screen when picked up. On being dropped, the brick falls away from the screen toward the floor under gravity. This sequence of interactions is captured in Figure 4.

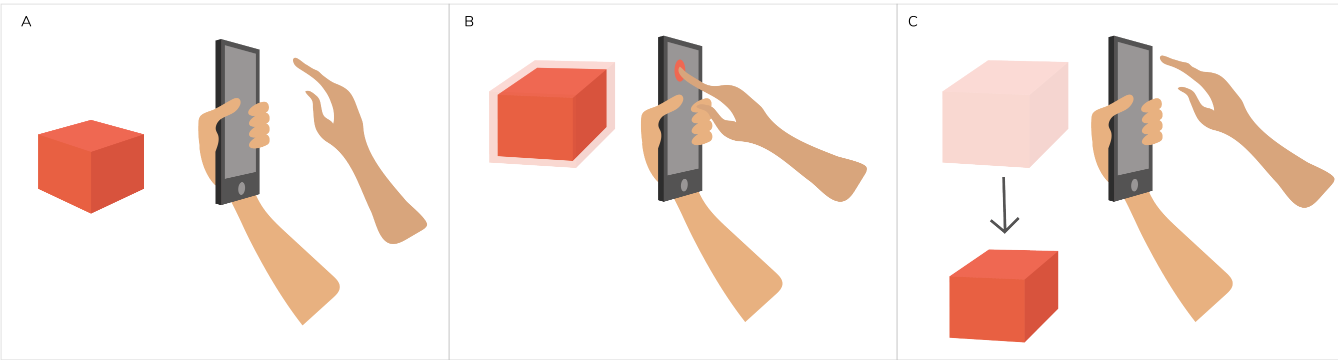

Figure 4: A graphic of the tap-and-hold interaction showing pick up (A), carry (B), and drop off(C). ©Po Bhattacharyya

Intrapersonal Interactions

> "When I can't find a piece, my frustration is directed at myself."

These interactions refer to internal deliberations going on in the mind of an individual player. Examples include players' emotion, cognition, and attention during gameplay.

Intrapersonal interactions became important while regulating players' mental state, particularly in the case of managing frustration. During our playtests, we noticed that players became visibly frustrated when they were unable to locate the bricks they expected to find. Often, this was because the bricks they sought were hidden behind other augmented objects. We couldn't address this issue directly, so we decided to allay players' frustration by adding extra bricks to the room.

Another intrapersonal interaction that presented design opportunities was players' delight. We noticed that many players experienced delight when they discovered or understood something new about the game. For example, some players expressed joy at figuring out how to pick up bricks on their own, in the absence of a formal onboarding process. One player felt delighted about suddenly discovering a number of previously obscured bricks during gameplay. Accordingly, we hypothesized that *Brick* encouraged players' curiosity about exploring an unfamiliar space with interactive elements.

Finally, we noticed that intrapersonal interactions were involved in players' interpretation of gameplay. We had designed *Brick* as a collaborative puzzle-solving game, but we noticed that some players interpreted the purpose of *Brick* differently. Many players reported an increase in breathing and heart rate during gameplay. A few players said that the game felt like a workout. Based on these findings, we argue that shared-world AR at the room scale presents interesting opportunities to design for players' bodily exertion during gameplay.

Multiplayer Interactions

> "During the game, I want to be able to pick up something and hand it to [my partner]."

These interactions involve an augmented object and both the players. Examples of *Brick*'s multiplayer interactions include collecting collaborative bricks and collaboratively defusing the bomb.

In designing multiplayer interactions for collaborative bricks, players' perceptions of personal space turned out to be important. In order to pick up collaborative bricks, players must approach it at close quarters. During our playtests, we noticed many players giggled and moved gingerly while picking up collaborative bricks with their partner. During the post-gameplay interview, these players reported feeling awkward while they were picking up collaborative bricks. Some players also reported that their feelings of awkwardness lessened with time, and that they became more comfortable with the collaborative interaction as the game progressed. Based on these findings, we argue that multiplayer interactions, especially those that require physical proximity, are an opportunity to invite players to explore such themes as intimacy and awkwardness with each other.

Moving beyond interactions that explicitly involve both players, we found that some aspects of single-player interactions became multiplayer experiences because the players were sharing the same physical space. One example is sound as a response to accomplishments in the game. We added auditory feedback when a player added an individual brick to the pattern. We noticed that these sounds elicited positive reactions not just from the player dropping off the brick, but their partner as well.

Interpersonal Interactions

> "When I couldn't find something, and [my partner] helped me find it, that was the best moment."

These are direct interactions between the two players, independent of the AR interface. Examples include conversations and physical contact between players.

While *Brick* does not explicitly require verbal communication between players, we noticed that many players naturally conversed with each other before and during the game. During our playtests, first-time players completed the game in relative silence. However, in the event of an unsuccessful round, returning players sought to talk to each other and come up with a strategy before they began playing. Players who began communicating before the game tended to maintain their camaraderie throughout gameplay and assisted each other with such tasks as finding missing bricks and collecting collaborative bricks more efficiently. These players also reported an increase in their comfort level with each other over the course of the session. Accordingly, we argue that a shared-world AR experience is an opportunity to use technology as a medium to enrich interpersonal communication.

Beyond verbal communication, players also showed awareness of each other even when they couldn't see what the other player was doing. During our playtests, we noticed that players would occasionally brush against each other while collecting and dropping off individual bricks. These maneuvers indicated that players were reacting to each other's bodies in ways that weren't required by the game. One player compared the game to dancing with a partner. Another player said *Brick* reminded them of another game, *Twister*, which involves extensive physical contact. Our findings indicate that shared-world AR offers opportunities to design for expressive latitude during gameplay.

Environmental Interactions

> "For the second round, I want to change the position of the wall so it's closer to the ground. It was too far away."

These are interactions between a player and their physical environment. Examples of environmental interactions involve navigation, collision avoidance, and supported movement.

While designing for the room scale, the positions of physical objects in relation to augmented objects turned out to be important. In early prototypes of the game, the pattern of empty slots was spawned by the game automatically, based on a predetermined algorithm that took the room's floor and walls into consideration. During our playtests, we noticed that players often struggled with the algorithmically-generated location of the pattern. For example, some players reported that the pattern was generated too close to an actual wall. Others complained that the pattern was too high up for them to reach. In general, players expressed strong preferences about the location of the pattern. So, we decided to give players control over where to place the pattern. In the current version of *Brick*, the host player can decide the pattern's location. The pattern appears at the intersection of the floor and the position where the host player taps the screen at the beginning of the game. The center of the pattern is 0.6 meters above the floor of the room.

Once the pattern is spawned, the bricks are spawned around it. A total of 28 bricks are spawned. The pattern has 20 empty slots, so the number of spawned bricks is slightly higher than the number of slots. The bricks are dispersed throughout the room to encourage players to locate, pick up, and place in the relevant space in the pattern. During our playtests, we noticed that players struggled with the locations of the bricks for two main reasons. First, some bricks were spawned at locations that were too high up for them to reach. Second, some bricks were spawned at locations that were inaccessible because of occlusion by walls and other physical objects. To address these issues, we decided to set definite bounds within which the bricks may appear; these bounds were designed to make the bricks more reachable and also to prevent occlusion by walls and physical objects.

Design Implications

As game designers, the interactions we created for *Brick* included both single-player and multiplayer interactions in AR. However, these interactions also had intrapersonal, interpersonal, and environmental implications. For example, the apparently single-player interaction of collecting an individual brick involves intrapersonal cognition, in which a player comprehends the gestures necessary to pick up, carry, and drop off the brick; interpersonal conversation, as when players help each other locate bricks during gameplay; and environmental awareness, since players navigate the physical space as they move.

We believe that the shared-world AR model provides a useful lens through which to design, evaluate, and improve upon interactions in a synchronous colocated AR experience involving multiple human participants. The success of such experiences is predicated upon the designer's ability to recognize and account for the various components and interaction categories we identify in our model. Here are four instances of our model's implications on the design of shared-world AR experiences.

Design for technological mediation. Our findings suggest that even the apparently analog aspects of our shared-world AR model could be technologically mediated. *Brick* includes some examples of such interactions. For example, at the beginning of the game, players have the option of choosing where in the room they should place the pattern of slots. Based on our observation that players sometimes struggled with patterns placed too close to walls, we view pattern placement as a technologically mediated environmental interaction in which players have to navigate their physical space. Moreover, during gameplay, players are able to approach their partner's bricks but cannot interact with them. In our playtest data, we saw that many players had trouble locating their own bricks. We therefore view non-interactive-brick detection as a technologically mediated interpersonal interaction in which players are incentivized to help each other out during gameplay.

Design for simplicity. Our findings indicate that phone-based mental models of interaction overrode physical models early in the game. For example, one participant said, "My first instinct was to tap on things. I didn't know that I had to approach things." Even after learning how to play, players needed ongoing technologically mediated cues to move their bodies. Therefore, whenever possible, the AR interactions themselves needed to be simple. For example, mobile-phone users are accustomed to selecting objects by tapping on the screen; therefore, it makes sense to leverage this expectation to create analogous interactions in the AR game space. If there are good design reasons for more complicated interactions, then players may need to be trained to perform them outside the shared-world AR context. For example, *Pokémon Go* trains players to perform their complicated flick-capture gesture as part of a single-player experience [23].

Design for physical proximity. When players are colocated, a shared-world AR system offers numerous opportunities for physical proximity and contact. As such, game designers need to make conscious decisions about encouraging or discouraging physical proximity to achieve desired results. For example, in *Brick*, we used a distance-sensitive hover state as well as a two-player tap-and-hold interaction to encourage proximity during gameplay. Brick's design forced players to stand close to each other during gameplay, and some of our playtesters went so far as to expect collaboration to be associated with physical proximity. For example, one player said, "I can hold [a collaborative brick], and as soon as you're holding it as well, that's when we pick it up." This implies the importance of designing technologically mediated interactions in ways that shape players' physical behaviors with each other, e.g., looking together at a screen or other objects in the environment.

Design for exertion. Our findings indicate that designers should account for exertion and fatigue while creating room-scale shared-world AR experiences. In the case of *Brick*, players exerted themselves in two ways: first, many players experienced a spike in heart rate while collecting bricks from around the room; second, some players who tried out the slam interaction (see Figure 3A) experienced fatigue in their wrist and lower arm from repeatedly slamming their phones to pick up bricks. These findings extend previous work in movement-based game design [20] to include shared-world AR experiences. Based on our results, we argue that designers need to make deliberate decisions about how players experience physical exertion during gameplay. While designing specific interactions in AR, both gross-motor involvement and frequency of repetition may be used to intentionally control difficulty and fatigue. For example, if a designer's goal is to reduce the chance of fatigue, they might choose to design repetitive interactions that do not involve extensive gross-motor movement. Conversely, if the designer's goal is to create a exergame, they might choose to add frequent interactions that require gross-motor movement while simultaneously allowing for expressive latitude [30].

5 FUTURE WORK

Our present work with *Brick* points at a number of fruitful avenues for future work in shared-world AR. First, we would like to explore more complex interactions with AR interfaces, including sensor-based interactions. Prototyping these interactions, such as our slam interaction, is relatively straightforward. The challenge is to make these interactions *discoverable* and *usable* in a game context where players may be attending as much, or more, to other players as they are to the AR interface. One idea would be to create multiplayer tutorials that teach users how to perform novel interactions; designed appropriately, these tutorials could leverage interpersonal dynamics to improve players' experience of the interface. In effect, the attention that players might naturally pay to each other would be become an asset rather than a hindrance to introducing complex, novel interactions.

Second, it would be interesting to extend the use of proximity and exertion as design materials for shared-world AR. Players' reactions to *Brick* point at the rich potential of studies that investigate people's of experience intimacy and awkwardness in a synchronous, colocated AR experience. For example, might physical proximity be used to heighten players' degree of comfort with each other after the game? What are the ethics of using a spike in heart rate to alter the relationship between potential romantic partners by making them feel more attracted to each other?

Finally, *Brick* is a two-player game. We would like to apply our model to explore shared-world AR systems that involve more than two players. One idea would be to extend *Brick* to three or more players who are working together toward the same goal. Another idea would be to create a new game in which teams of players compete against each other for the winning spot. In both these cases, it would be interesting to explore how the current model accounts for the introduction of additional players to a shared-world AR environment.

In conclusion, we view shared-world AR as a valuable addition to existing modalities of social gameplay, both for its ability to ground people in their physical reality as well as its potential to connect people with each other. We look forward to research- and design-based applications of our model, as well as to new technologies that might expand the possibilities in the domain of multiplayer AR.

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