Beyond Augmented Reality, Towards Augmented Physicality: Gaming with Tangible Embodied Interactions

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Fig. 1. Left: Camera View; Right: Player's Headset View.

As Augmented Reality (AR) continues to advance and permeate everyday life, the importance of designing effective and engaging AR experiences is increasingly important. This study explores the augmentation of everyday objects as embodied interfaces in a tower defense game played using the Meta Quest 3. We compared player experiences using hand gestures in AR, with playing using a Tangible Embodied Interface (TEI). A 3D-printed cube with magnetically attached codes was created to prototype the combined AR/tangible interaction modality. Ten participants played both versions of the AR game and then took part in an interview. We found that the use of tangible objects significantly enhanced players' sense of control, engagement, and overall experience. Participants reported that the use of tangible interfaces in AR facilitated more intuitive and natural interactions which resulted in increased immersion and enjoyment. These findings contribute to the understanding of tangible AR interactions and potential implications for game design.

CCS Concepts: • **Software and its engineering** → **Interactive games**; • **Human-centered computing** → **Mixed / augmented reality**; **Interaction devices**.

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Manuscript submitted to ACM

Additional Key Words and Phrases: Tangible Embodied Interface, Augmented Reality, Video Games

ACM Reference Format:

Qingxuan Yan, Michelle Adiwangsa, and Anne Ozdowska. 2024. Beyond Augmented Reality, Towards Augmented Physicality: Gaming with Tangible Embodied Interactions. In *Proceedings of OzCHI 2024: Beyond Being Human (OzCHI '24).* ACM, New York, NY, USA, 22 pages. https://doi.org/XXXXXXX.XXXXXXX

1 INTRODUCTION

Augmented Reality (AR) is a technology that overlays virtual objects onto the real-world environment [2]. Compared with other reality-altering technologies such as Virtual Reality (VR), which completely immerses users in a synthetic environment, AR supplements reality rather than replacing it. This fusion opens up a wide range of possibilities for enhancing human experiences across various domains, such as education [13], medicine [6], product design [22], and gaming [15]. As AR evolves, it presents new challenges for designing effective and engaging user experiences that meet the interaction expectations of diverse users, particularly in gaming, where intuitive and immersive interaction are crucial. One key challenge is exploring how different interaction methods in AR can influence user experience, which is the focus of this study.

A recent systematic review by Spittle et al. [31] provides a comprehensive analysis of the current state-of-the-art interaction techniques in AR. The most commonly used interaction modalities are freehand gesture interaction and hardware-based input. This modality typically involves handheld controllers or other peripherals to provide input with 6 degrees of freedom (6DOF). Freehand gesture interaction offers an intuitive and natural way for users to interact with virtual content, but prolonged use may lead to fatigue. On the other hand, hardware-based input provides precise control and haptic feedback, but requires users to hold additional devices, which may hinder the sense of immersion. For AR to become accessible for a wider range of users these kinds of usability challenges will need to be overcome.

An interaction paradigm that combines the benefits of both freehand and hardware-based input is tangible interaction. Tangible AR interfaces allow users to manipulate physical objects to interact with virtual content, providing a more intuitive experience [34]. Leveraging the inherent properties and action possibilities of physical objects, known as affordances [8], tangible AR interfaces enhance the user's sense of presence and facilitate natural, embodied interactions. By incorporating physical objects into AR interfaces, users can interact with virtual content in a more familiar and natural manner, as they would with real-world objects. This can lead to a heightened sense of immersion and a more engaging user experience [11].

However, despite the potential benefits of tangible interaction in AR, there is still a lack of understanding on how the incorporation of more diverse and novel tangible objects with enhanced three-dimensional and tactile qualities affects user experience, particularly in the context of AR gaming. Although the concept of tangible AR has been around for over two decades since it was first introduced by Kato et al. [14], most research has focused on using simple 2D tangible objects like cards or markers that lack a strong three-dimensional and tactile presence [27, 34]. While cards and 2D markers are easy to implement and track, they do not provide rich tactile feedback or afford complex manipulations and do not fully capitalise on the potential of tangible interaction in AR [11]. Moreover, they may not be suitable for all types of AR applications, particularly those that require direct manipulation of 3D virtual objects [18]. Therefore, there is a need to explore the use of more diverse and meaningful tangible objects in AR interfaces, and to investigate how they influence user experience and interaction outcomes, especially in the domain of AR gaming.

This research aims to address this gap by investigating the role of tangible objects in shaping user experiences within AR environments. Specifically, we focus on an AR tower defense game due to its frequent and diverse user interactions.

This genre provides a rich design space to explore interaction modalities and their impact on player experience. The primary research question guiding this study is: **How does the integration of tangible objects in an AR game influence player experience when compared to a digital hand-gesture-based interface?** To address this question, we have set out the following objectives: (1) to design and develop two versions of an AR tower defense game, one with tangible object interaction using 3D-printed cubes as 3D markers, and another with a purely digital gesture-based interface; (2) to evaluate player experiences through gameplay metrics and interviews; and (3) to provide actionable insights and design implications for AR game developers and designers.

The significance of this research lies in its potential to contribute to the growing body of knowledge on tangible AR interaction and its implications for game design. By providing a comparative analysis of player experiences with and without tangible objects, this study aims to offer valuable insights into the benefits and challenges of incorporating tangible elements in AR gaming. Furthermore, this study advances the use of AR markers by exploring the transition from 2D to 3D tangible objects, demonstrating the feasibility of 3D markers and their potential impact. Finally, the findings of this research may inform future design decisions and inspire new avenues for creating engaging and immersive AR gaming experiences.

2 LITERATURE REVIEW

2.1 Interaction Modalities in AR

Recent literature has identified several primary interaction modalities in Augmented Reality (AR) environments. Spittle et al. [31] categorises AR gestures into five categories, including, freehand gestures, head-based input, speech-based input, hardware-based input, and multimodal interaction. Freehand gestures, the most common input method for head-worn AR devices, allow users to interact with virtual content using predefined or unconstrained hand movements. While intuitive and suitable for entertainment applications, prolonged use of freehand gestures may lead to fatigue [20]. Head-based input, utilising gaze direction and head orientation for pointing and selection tasks, offers a hands-free experience but may lack the precision and naturalness of hand gestures [31]. Speech-based input, mainly used for abstract tasks and discrete commands, can compensate for the ambiguities in natural language when combined with head-based input. However, the robustness of speech recognition remains a challenge, along with concerns about privacy and social acceptance [17]. Hardware-based input, involving handheld controllers or other peripherals for 6DOF input, provides haptic feedback and high precision but requires additional hardware, which makes it less natural than other methods. Multimodal interaction, combining various input modalities, can leverage the strengths of different inputs and enhance interaction accuracy and capability, but understanding how to balance and switch between input modalities remains an area of ongoing research.

2.2 Tangible AR Interfaces

While these interaction modalities have been widely explored in AR research, there is a growing interest in tangible interaction, which bridges the gap between the virtual and physical worlds. Tangible AR (TAR) interfaces, first introduced by Kato et al. [14], utilise physical objects to interact with virtual content in AR environments. By displaying virtual elements on tangible items, these items become controllers for manipulating virtual data. Kato et al. [14] demonstrated that integrating tangible card-based interfaces with AR could significantly enhance the experience of traditional board games, highlighting the transformative potential of AR in gaming.

Tangible AR interfaces can allow the design of simple yet effective tools and operations to interact with virtual objects in AR environments. They give users control over virtual information by allowing them to interact with physical items also. These tangible objects are usually marked with paper or cards that can be tracked in 3D space to locate virtual content [4]. Using physical objects as a method of control can ease the difficulty in user operations as the manipulation of physical objects is often intuitive. The embodied control via tangible objects and responsive feedback can provide users a clear understanding of their actions [9].

Using tangible AR interfaces for teaching can motivate and facilitate learning activities. For example, complex chemistry knowledge can be transformed into vivid graphics with a physical object as an exciting new avenue to learn[21]. Monteiro et al. [24] presented a comprehensive analysis of tangible AR interaction modalities in their work "Teachable Reality". They developed a system based on the trigger-action authoring model to explore the diverse inputs and outputs for creating immersive AR experiences. While their research provides a holistic view of potential AR interfaces and categorises input modalities into objects, human interactions, and environment, it does not specifically focus on the application of tangible objects in their impact on user experience.

Tangible AR interfaces have also been used in museums to support interactive experiences with cultural artifacts [3]. They represent a useful way to enhance museum experiences since they bridge the gap between physical and virtual information. Examples of tangible interfaces in museums include the use of touchscreens and physical replicas to enhance users' perceptions of museum artifacts [29]. Such tactile encounters support user interactions with museum artifacts with a direct approach [23]. In many cases, virtual content such as 3D models, videos, and audio recordings are superimposed on these tangible interfaces to introduce artifact information. This compensates for the fact that artifacts cannot be touched and observed from different perspectives and allows people to explore artifact knowledge through the rich digital affordances of multimedia [26].

Xu et al. [33] investigated the effects of two tangible AR interfaces, CubeMuseum AR and Postcard AR, on cultural heritage learning and museum gifting experiences. Through a rigorous experimental design combining quantitative and qualitative methods, they obtained valuable insights and design guidelines. The research demonstrated the positive impact of combining AR with physical objects on users' learning motivation and engagement, thanks to the rich digital affordances, intuitive tangible interactions, and the hybrid design. Moreover, the optimised version of CubeMuseum AR, which incorporates gamification and visualisation mechanisms, significantly enhanced users' learning motivation, engagement, and outcomes, revealing the important value of gamification in cultural heritage learning.

2.3 Tangible AR in Gaming

Building on the foundational work of Kato et al. [14], Huynh et al. [12] introduced "Art of Defense (AoD)," a cooperative AR tower defense game. Their exploratory user study, involving twelve participants, used interviews to gather qualitative feedback, yielding strikingly positive responses. Notably, participants praised the tangible interface, citing it as one of the game's standout features. Most participants found the game enjoyable and engaging, with a desire to play again. Such findings underscore the potential appeal and acceptance of tangible interfaces in AR gaming. However, it's important to note that Huynh et al. [12]'s research primarily focused on the social communication between players. Their exploration into tangible interfaces, while insightful, was limited in scope and depth. As a result, there remains a substantial gap in understanding the full implications and nuances of tangible interactions within AR gaming.

Kim et al. [15] developed "Bubbleu," an AR pet breeding game that uses object detection as a primary interaction. They explored how game design elements, specifically Ambiguity, Transparency, and Controllability, can enhance the user experience in TAR environments, especially when object detection might not always be accurate. For example, Ambiguity helps hide errors, Transparency highlights them to guide users, and Controllability gives players more control over in-game uncertainties. These design insights offer valuable guidance for enhancing tangible AR game experiences.

In the context of AR gaming, the use of tangible objects as input devices has shown promising potential. Li et al. [19] conducted a mixed-design study with 32 children aged 7-8 years old to compare the effects of different interaction types (screen-touch vs. tangible) on children's motivation and engagement in an AR mathematics game. The authors found no significant difference in motivation between the two interaction types based on quantitative measures. However, qualitative interviews revealed that children enjoyed exploring and practicing with the tangible interface, finding it more interesting and fun, particularly after mastering the controls. The authors suggest that tangible interaction can facilitate children's development of fine motor skills and provide a more immersive experience, despite some limitations such as the need for larger physical space and potential for fatigue during extended gameplay.

Havrez et al. [9] proposed a structured framework for developing tangible interaction applications. This model categorises physical objects based on their representation of digital functions, information, or scenery, and emphasises the importance of haptic and digital feedback to enhance interactivity. This model was applied to a serious game focused on microbiological waste sorting, utilising tangible objects on an RFID tabletop. The game associates physical objects with digital elements, provides structural constraints, and leverages visual and haptic feedback to guide users in executing and evaluating actions. This design model and its implementation offer insights for exploring tangible AR in cultural heritage learning. It illustrates how to associate domain knowledge with physical objects and digital elements, utilise multiple forms of feedback to enhance motivation and engagement, and consider structural constraints for intuitive interactions.

2.4 Conclusions

The reviewed literature highlights the potential of tangible interaction in AR environments, particularly in education, cultural heritage, and gaming. Previous research has demonstrated the benefits of tangible AR interfaces in enhancing user engagement, motivation, and learning outcomes through embodied control, natural mapping between physical and virtual elements, and rich sensory feedback. However, existing applications have primarily focused on domains such as education and cultural heritage, often using simple and relatively flat tangible objects like cards or markers that lack a strong three-dimensional and tactile presence.

There is an opportunity to explore the use of more diverse and novel tangible objects with enhanced three-dimensional and tactile qualities in AR gaming and to study their impact on user experience. The current study aims to address this gap by comparing tangible and gesture-based interaction in an AR tower defense game, using a purposefully designed tangible interface that incorporates more advanced physical objects. By investigating the effects of this novel tangible interface on player experience, motivation, and engagement, this research contributes to the growing body of knowledge on tangible AR interaction and its implications for AR game design.

3 METHODOLOGY

We primarily employed a qualitative approach through a comparative user study to assess the impact of tangible objects within an AR game, with quantitative data serving as a supplementary tool. We designed an AR tower defense game with two versions, a control game and an experimental game. In the control version of the game players only used hand-gestures, and in the experimental version players incorporated a tangible object into the interaction. Images of each game can be seen in Figure 4. All participants played both versions of the game.

The control, hand gesture game data formed our baseline data collection and provided a benchmark for understanding player experiences during traditional AR game play. By having this control game, direct comparisons can be made with the experimental tangible-integrated version. The baseline game and the experimental game are identical in all other aspects, such as game content and difficulty, with the only difference being the interaction modality. The comparison aligns with the method of "contrastive analysis," widely used in human-computer interaction research to evaluate the impact of different interface elements on user experience [25].

In-game quantitative data was collected. This data provided us with measurable indicators of player experience. Qualitative data was gathered through interviews and observations. Interview data offered in-depth insights into players' subjective perceptions of both gaming modalities. We obtained insights by comparing and analysing the feedback received from participants across the two versions. The first author made observation notes while participants played each version of the game. Our research received approval from the university's human research ethics committee and an informed consent was obtained from all participants.

3.1 Materials

The control and experimental games each had the same three consecutive levels, where the goal of each level was to defeat all incoming enemies before they reached the last coin on the map (see 'Defeat Condition' in Figure 2). One catapult was provided as the player's main attack mechanism, where the catapult would automatically attack the nearest enemy until it is out of ammunition, in which case the player has to interact with the catapult to 'reload'. At the end of each level, the player earns the remaining coins as resources, and may use them to purchase upgrades for the catapult.

In the experimental condition players needed to interact with a palm-sized cube, measuring 5x5x5 centimeters to upgrade mechanisms and reload the catapult (see Figures 3 and 4). Players could interact with the cube by physically moving its position, rotating the cube, placing attachable upgrade pieces, and shaking the cube. In the control version, players interact with the virtual catapult using conventional hand gestures, such as pinching to drag and drop.

3.2 Development

The AR game was developed using Unity, a widely-used game engine with robust support for AR/VR applications. Given that the Meta Quest 3 was utilised as the HMD (Head-Mounted Display) for its passthrough feature in this study, we employed the Meta XR All-in-One SDK provided by Meta to facilitate AR functionalities within Unity. This SDK offers readily available APIs for implementing essential AR features such as hand tracking, which were crucial for our application's interaction.

The game development process primarily involved level design, 3D modeling, animation, and game mechanics. Models and animations were created in Blender, with additional assets sourced from the Unity Store. The game mechanics were implemented using C#, where we scripted the core gameplay elements such as player interactions, object behaviors, and game logic.

Additionally, we integrated the ArUco tracking system to enable interaction with physical objects. ArUco is a type of marker similar to a QR code, and we utilised the OpenCV API in Python to detect and track these markers on physical objects. By capturing the position and orientation of these objects on the screen, we were able to map their coordinates to the actual gameboard using Homography Transform. The data was then broadcast to the Unity engine via UDP, where the corresponding virtual objects' transforms were adjusted in real-time to ensure synchronisation between the physical and virtual environments.

3.3 Study setup

For this study, we utilised a Meta Quest 3 headset. The tangible cube and its attachable pieces for upgrading were 3D-printed. For easy attachment, they were fitted with magnets. Additionally, the following equipment was also used (see Figure 5).

- **Meta Quest Link Cable:** Used to connect the headset to a laptop, this cable ensured better casting with lower latency and higher stability.
- **Wide-Angle Camera:** During game experiment sessions, this camera detected and located tangible objects on the game board and recorded participant interactions.
- **Desktop Boom Arm Stand:** This stand held the wide-angle camera in an overhead position, providing a top-down view.
- **ArUco Markers:** These printed markers were used to accurately position and identify tangible objects on the game board.
- **Signboard:** A 500 mm x 770 mm signboard was used as the game board, with ArUco markers affixed to each corner for consistent setup and stable tracking.

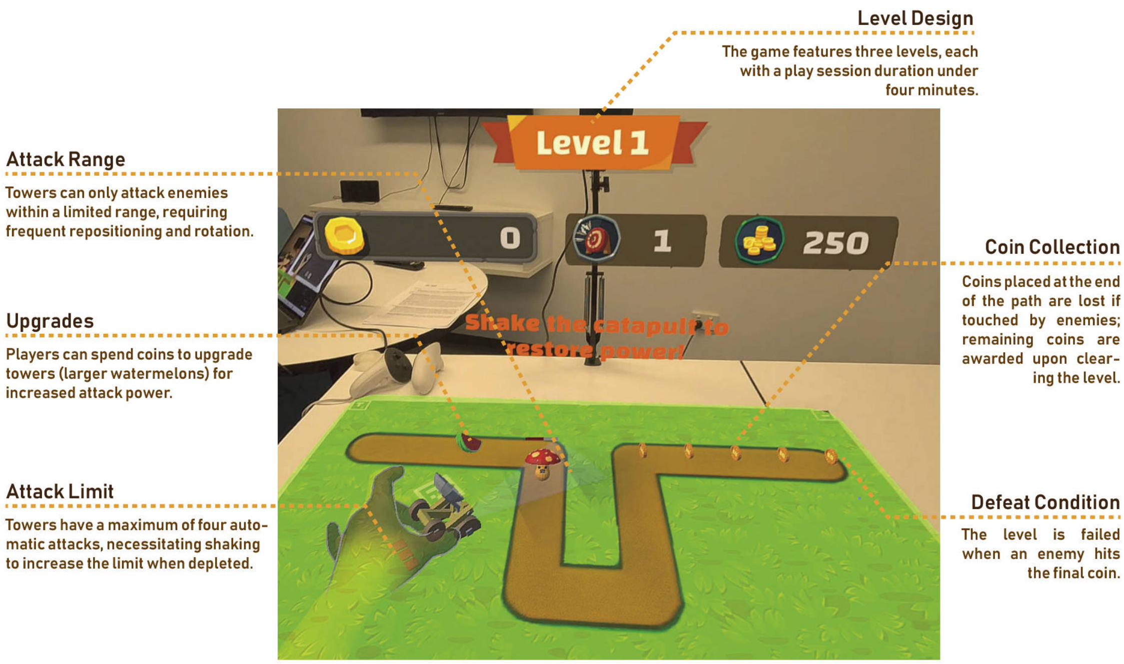
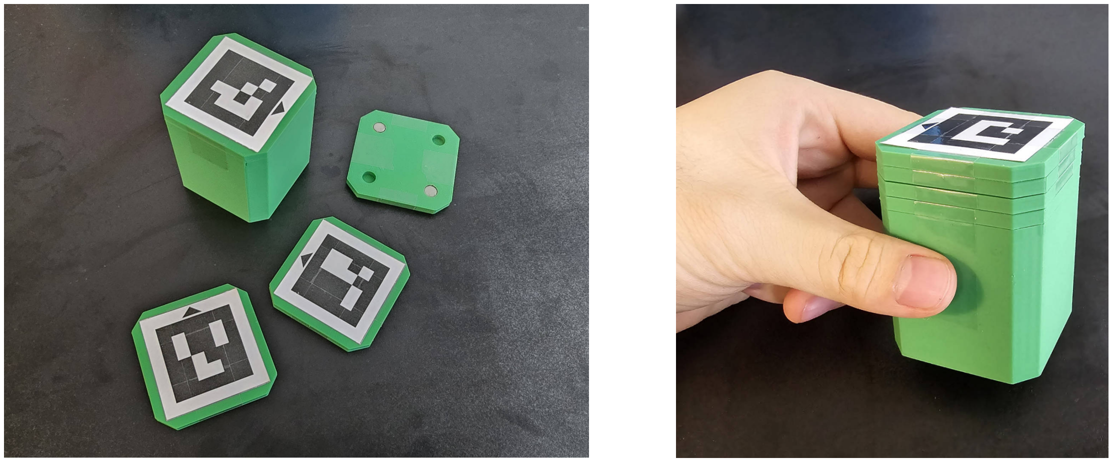


Fig. 2. Final Game Presentation (Tangible Version)

3.4 Participants

We recruited 10 participants, aged between 20 and 25 years, with an equal gender distribution (5 male, 5 female). All participants had some previous experience playing video games but had no prior experience with similar AR tower



(a) Cube and Attachments (b) Cube with All Pieces Attached

Fig. 3. 3D-Printed Tangible Objects

defense game. Additionally, none of the participants had a history of motion sickness or epilepsy. Importantly, they had no prior experience with AR/VR gaming, especially in interactive settings. Their exposure to AR/VR was minimal, with only two participants having up to one hour of passive experience watching VR immersive videos.

Participants were recruited through a combination of online and offline methods, which included posting on social media groups related to AR and gaming, distributing posters on public social platforms, and snowball sampling (asking participants to recommend others who might be interested).

3.5 Procedure

We conducted user studies with each participant individually. Before the experiment began, participants were informed about the purpose of the study and provided with a brief introduction to the Quest headset, including its features, how to wear it, and time to get accustomed to the device and its hand gesture interaction. There were three parts of our study, namely:

(1) **Gaming Experiment Session I (5 minutes):** Participants were assigned to start with either version 1 (hand gesture-based game) or version 2 (tangible interaction-based game) based on their participant ID (odd-numbered IDs began with version 1, while even-numbered IDs began with version 2). This included time for brief instructions and guidance on gameplay mechanics and interactions.
(2) **Gaming Experiment Session II (5 minutes):** Participants then played the second version of the game that they did not play in the first session.
(3) **Participant Interview (15 minutes):** A one-on-one interview was conducted, focusing on the participants' experiences and perceptions during both game sessions.

3.6 Data Collection

This study employed multiple data collection methods to gather information about participants' experiences and interactions with the AR tower defense game. The primary data collection method was qualitative, involving interviews

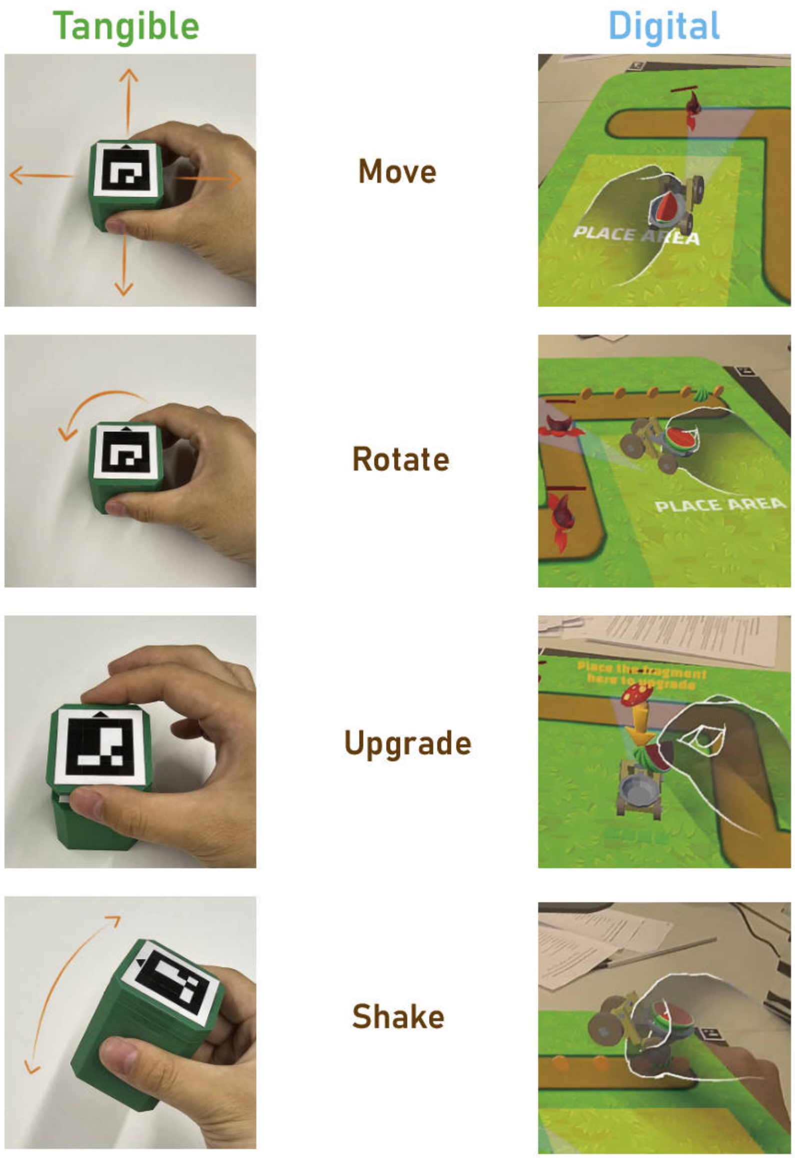


Fig. 4. Comparison of Interaction Methods: Tangible vs. Gesture-Based

and observations. Additionally, we collected quantitative in-game metrics to complement the qualitative data. These methods were chosen to provide a well-rounded understanding of participants' subjective experiences (interviews) and objective behaviours (through observations and gameplay metrics).

3.6.1 Interviews. Semi-structured interviews were conducted with participants after they have completed both gameplay sessions. The interviews aimed to gather in-depth and qualitative insights into participants' experiences, preferences,

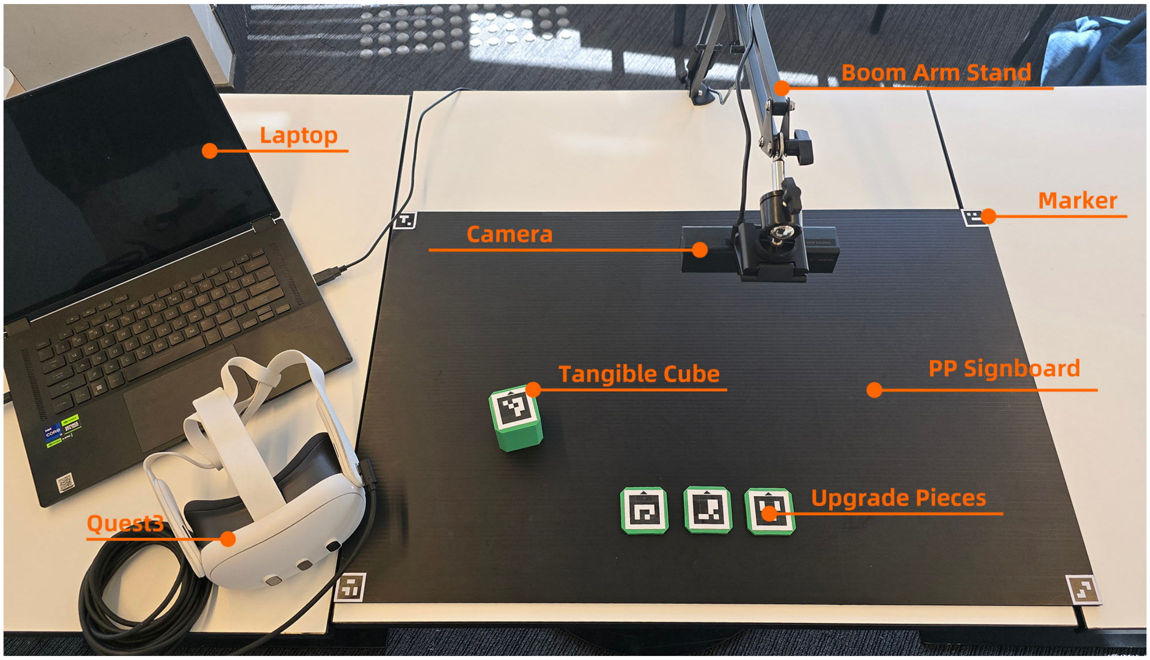


Fig. 5. Final Setup for Tangible Interaction Version

and suggestions for improvement. The questions were designed to encourage participants to reflect on and compare their experiences with the hand-gesture and tangible object versions, focusing on aspects such as engagement, immersion, control, learning curve, and overall enjoyment. Given the small sample size of our study, these in-depth interviews were particularly suitable for obtaining rich, detailed feedback and understanding the nuances of participants' experiences. The questions were organised into themes that correspond to key aspects of player experience, such as immersion, challenge, and control, which have been identified as important factors in gaming research [32]. Participants were prompted with the following interview questions:

- What was your first impression when you started playing the AR tower defense game?
- How did your experience differ when playing with tangible objects compared to the purely digital version?
- In which version of the game did you feel more immersed or engaged, and why do you think that was?
- Did you feel challenged by the game? Which version of the game did you find more challenging for your skill level?
- Do you think using tangible objects in the AR version enhanced or hindered your sense of control while playing the game?
- Based on your experience with both versions of the game, what aspects did you like or dislike in each version?

3.6.2 Observations. The first author also observed participants' behaviours, reactions, and interactions during the gameplay sessions. These observations focused on capturing non-verbal cues and natural interactions that may not be apparent through self-reported measures alone. A structured observation protocol was used to ensure consistency and reliability across observations. This protocol included a checklist of specific behaviours and reactions to look for, as well as space for open-ended notes and descriptions. We observed the following aspects from participants:

- Handedness: Do participants use their left hand, right hand, or alternate between hands when interacting with the tangible objects?
- Ease of use: Do participants appear to struggle or show signs of frustration when manipulating the tangible objects (e.g., furrowed brows, sighs, verbal expressions of confusion or annoyance, and/or request for help or clarification)?
- Reaction times: Are there noticeable differences in participants' reaction times when using hand gestures versus tangible objects?
- Emotional responses: Do participants exhibit more positive or negative emotional reactions (e.g., smiling, frowning, or exclamations) when playing with tangible objects compared to hand gestures?
- Postural changes: Do participants lean in, sit back, or change their posture when interacting with tangible objects versus hand gestures?

3.6.3 Gameplay Metrics. Objective gameplay metrics was gathered from the screen recordings of participants' gameplay sessions. By comparing these metrics between the hand-gesture and tangible object versions of the game, we could determine whether tangible objects have a measurable impact on player performance, engagement, and success [7]. This objective data complemented the subjective experiences reported in the interviews, providing a more comprehensive understanding of the role of tangible interactions in AR gaming. The metrics were:

- Whether the game was completed
- Time taken to complete the game
- Number of coins gathered
- Number of times the tower was rotated and moved
- Time taken to eliminate the first enemy
- Frequency of energy replenishment through shaking or hand gestures

3.7 Data Analysis

Gameplay metrics were extracted from the screen recordings of participants' gameplay sessions and quantified. The analysis of these objective measures complemented the subjective data from the interviews. It also and provided a more comprehensive understanding of the impact of tangible interactions on player experience and performance.

The qualitative data collected through semi-structured interviews and observations were analysed using a six-phase thematic analysis approach [5]. This involved: (1) familiarising the data; (2) generating initial codes; (3) searching for themes; (4) reviewing the themes; (5) defining and naming themes; and (6) producing the report. We utilised colour-coding and the "scissor and sort" technique, where the iterative coding process involved highlighting relevant segments of text with different colours based on their relevance to specific themes or ideas that emerged. The coded extracts were physically cut out and sorted into piles representing potential themes. To ensure the reliability and consistency of the coding, iterative reviews of the coded data were conducted. Additionally, the final themes were discussed with the second and third authors to reduce potential bias and refine the identified themes.

The video recordings, including first-person perspective from the head-mounted display and top-down view of player hand interactions with tangible objects, were also analysed to support and enrich the qualitative findings. Key moments, such as instances of player engagement, challenges, or interesting interactions, were identified and described in detail to provide additional evidence for the identified themes.

4 RESULTS

4.1 Gameplay Metrics

A comparison of the key gameplay metrics between the digital and tangible versions of the game showed that participants generally performed better across various metrics on the tangible interaction version compared to the digital interaction version (see Table 1):

Metric	Digital Version	Tangible Version
Completion Rate	7/10	10/10
Time to Complete (minutes)	4:10	3:43
Coins Gathered	≈ 500	≈ 600
Number of Times the Catapult was Rotated and Moved	68*	45*
Time to Eliminate the First Enemy (seconds)	30	24
Frequency of Shaking	19	16

Table 1. Gameplay Metrics for Digital vs Tangible Versions.
*Consecutive rotations are counted as a single action.

As shown in Table 1, the completion rate was higher for the tangible interaction version, with all participants successfully completing the game, compared to only 7 out of 10 participants in the digital interaction version. Participants using tangible objects also took less time on average to complete the game, finishing in 3 minutes and 43 seconds compared to 4 minutes and 10 seconds for those using hand gestures. In terms of coins gathered, participants collected approximately 600 coins on average with tangible objects, compared to 500 coins using hand gestures, suggesting a potential trend toward more effective gameplay as players were able to eliminate enemies more quickly with the tangible interaction. Furthermore, the tangible object version resulted in fewer rotations and movements of the catapult (45 times) compared to the digital version (68 times), indicating a possible trend of more efficient control with tangible objects. Participants were also quicker to eliminate the first enemy using tangible objects, taking only 24 seconds compared to 30 seconds with hand gestures, which suggests that tangible interactions allow for faster responses. Additionally, the frequency of energy replenishment was slightly lower in the tangible version (16 times) compared to the digital version (19 times), suggesting a smoother, more seamless gameplay experience with fewer interruptions. While statistical analysis was performed on the quantitative data, the current sample size is not sufficient for making statistically significant claims. It is also out of the scope for this paper.

4.2 Interview themes

We identified three overarching themes that encapsulated the key aspects of participants' experiences and perceptions, related to: (1) enhanced immersion and realism; (2) intuitive control and precision; and (3) learning curve and challenge.

4.2.1 ***Theme 1: Tangible interface can facilitate enhanced immersion and realism.*** We found that the tangible interface in the game enhanced players' sense of immersion and realism to a certain extent. In the interviews, we explained to participants that immersion is the extent to which players feel completely absorbed and involved in the game, while realism denotes how lifelike and authentic the virtual world appears. For many participants, physically holding and manipulating an object made the virtual world feel more believable, as if they were truly part of it:

> "Having a real object in your hand, rather than just waving in the air, makes you feel more genuinely present and engaged. (Participant #6)"

Participant #6 also mentioned that using gestures in the air felt empty and fake, making it hard to stay immersed. Participant #2 explained that, on a psychological level, the lack of immersion in gesture-based control was due to the fear of looking silly if others saw them wearing a headset and waving their hands in the air. This concern made it hard for them to feel fully immersed:

> "Having a physical object is a bit more fun, because it makes me feel like I'm actually controlling something, letting me grasp it. This way, in addition to the visual experience, it also adds a tactile sensation. (Participant #1)"

The sense of immersion was often attributed to the tactile feedback provided by the tangible object. Participants reported that the weight and solidity of the physical object gave them a stronger sense of connection to the game world (e.g., Participants #4 and #8). Moreover, several participants noted that the tangible interface allowed for continuous operations, whereas gesture controls felt discrete and disjointed (e.g., Participants #1, #4 and #7). This seamless interaction with the physical object helped participants stay focused on the game:

> "The first version, with gesture controls, sometimes made me feel frustrated due to the delay, which affected the immersion. But with the second version, the smooth operation allowed me to focus more on the game itself. I think this significantly enhanced the immersion. (Participant #8)"

It is important to note that immersion is a very subjective concept, and everyone experiences it differently. A few participants felt that the difference in immersion between the two interfaces was not very significant. Participant #4 mentioned that the tangible interface could be distracting at times, as the need to manipulate a physical object could sometimes draw attention away from the game world. Specifically, when they had to place a piece onto the 3D-printed cube to upgrade the tower, they momentarily felt pulled back into the real world, which disrupted their sense of immersion:

> "Actually, the difference is not that significant. In the purely virtual version, I feel completely absorbed in the game. But with the tangible prop, the action of grasping the object (pieces for upgrading) might divert my focus a bit. (Participant #7)"

Additionally, when asked if there were any aspects of the tangible interface that might affect their sense of immersion, Participant #7 mentioned:

> "If the props could be designed to resemble the in-game buildings more closely or if the game's constructs were also changed to a block-like shape, it might feel more cohesive. (Participant #7)"

The participant further pointed out that the current use of a simple cube and flat pieces for upgrades did not match the in-game catapult and watermelon shapes. All participants were asked about this issue. Nine other participants noted that this did not affect their perception of the game. They mentioned that in the AR gaming environment, they could not clearly see the physical object's details. As long as there was something to grab, hold, and feel the weight of, they did not notice the difference in shape. They felt that what they were holding in their hand was what they saw in the game. For most participants, the realism of the tangible object did not significantly impact immersion in the AR environment.

Participants also shared some ideas for enhancing immersion in future tangible AR games. Participant #1 and #9 mentioned that using gravity sensors and linear motors could provide more force feedback when interacting with physical objects. One example was to add vibrations when shaking the object. Participant #10 suggested adding pressure sensors to the physical object to turn the current automatic attack into a manual one, such that when pressing to manually attack, the object could also shake. Meanwhile, participant #4 suggested that tangible objects should vary slightly to reflect differences in game elements. This way, players could physically, not just visually, feel the tower upgrades, which would undoubtedly enhance immersion further.

4.2.2 ***Theme 2: Tangible interface offered more intuitive control and precision.*** All participants mentioned that the tangible interface offered more intuitive control and higher precision compared to the gesture-based interface. Specifically, they felt that physically manipulating the object allowed for more accurate and natural interactions with the catapult tower, especially for rotation operations. In this context, "intuitive" can be a subjective or ambiguous term. We define it as the ease and naturalness with which participants could perform actions without needing conscious thought.

> "I think tangible interaction would be better, because it allows me to more precisely control the position of the catapult and its distance from the enemy’s path. Virtual gestures may not be as intuitive in this regard. (Participant #4)"

Participants found it easier and more natural to adjust the catapult’s position and angle using the tangible prop. This precise control was partly because the tangible object is on a stable surface. They could make small adjustments with light movements or slight rotations. In contrast, gesture-based controls often caused larger, less precise changes due to the limitations of gesture recognition systems. In a gesture-only AR interaction, moving the catapult requires three steps: (1) grab it with at least the index finger and thumb; (2) move the hand (may also involve wrist and arm movements); and (3) release it. During this process, the arm is in the air, which makes it prone to shaking and results in unintentional movements. This often means needing multiple adjustments to get the desired position, reducing overall efficiency and accuracy:

> "In the tangible version, I can directly move the model of the catapult. For example, if I want to move it from here to there, I can just grab it and move it over, which feels more convenient. With the virtual gesture interaction, I have to pick up the catapult first, put it down, and may need to adjust the angle in between, which is less intuitive and accurate. (Participant #5)"

Using tangible objects appears to offer a more accessible and comfortable experience compared to the gesture-based version. One participant highlighted this by noting the ease of real-time control with physical interaction:

> "I find myself feeling more relaxed psychologically when playing the version with physical interaction, because I can adjust its position and angle at any time. But with the hand-gesture version, because it’s purely virtual and not as easy to operate, I tend to place the catapult in position first and then slowly adjust the angle. It feels like the version allows for more real-time control. (Participant #6)"

Through observation, we also noticed this clear difference. When using gestures, almost all players would adjust the position and angle of the catapult, then remove their hands and just watch. They would only make further adjustments when the enemies were about to leave the attack range. In contrast, with the tangible object, more than half of the participants kept holding the physical prop, continuously adjusting the catapult’s angle in real time to keep it aimed at the enemies. This way, the enemies rarely moved out of the attack range. This is precisely what "real-time control" means in this context.

The intuitive feel of tangible interactions may stem from their closer resemblance to everyday object manipulation. One participant described this naturalness:

> "Tangible interaction is still closer to life experience. After all, our first reaction to adjusting the position of an object is to grab it. Gesturing is indeed not that intuitive. Although gesturing is also something we do every day, it still feels awkward and not suitable for gaming in AR. (Participant #7)"

One participant vividly highlighted the difference in control precision between the two interfaces:

> "The first version is like when the steering wheel fails while driving. If you deviate slightly, it will lose control and then violently turn to the other side, making it unstable to control. (Participant #5)"

This analogy underscores how gesture-based interaction often results in larger, unintended adjustments when only a slight tweak is needed. In contrast, the tangible object allows for precise, intentional movements. Gesture-based control offers a more discrete form of interaction, while the tangible interface provides continuous, smooth adjustments. However, it is worth noting that perceptions of sensitivity and accuracy might vary from person to person. Participant #8 expressed a different perspective, indicating that gesture recognition felt more precise and reliable. This participant argued that gesture recognition technology is already quite mature, and they could not fully trust the algorithm for recognising physical objects. The participant was concerned about whether the physical objects could be consistently and robustly recognised when controlling them. Despite this reservation, the majority of participants still found the tangible interface to be superior in terms of operability, apart from the delays in object recognition due to technical reasons.

4.2.3 ***Theme 3: Tangible interface is associated with a shorter learning curve and lower perceived challenge.***

Participants had varying opinions on which interface was easier to learn and master. Most participants found the tangible interface more beginner-friendly, as it closely resembled real-world interactions.

> "The second (tangible) version is easier to pick up. I think the first one will be a bit more difficult, because it doesn't have a physical object and lacks tactile feedback. Additionally, it might be a habit issue. For those of us who have played with a keyboard and mouse since childhood, it's a bit hard to accept operating completely in the air. (Participant #2)"

The familiarity and tactile feedback provided by the tangible interface made it easier for many participants to grasp the controls and quickly adapt to the game mechanics.

> "If you want to fully complete the virtual version, it will be relatively difficult. The tangible version will be simpler for me, because the operation is more responsive. (Participant #1)"

This participant's feedback suggests that using tangible objects might actually influence the perceived difficulty of the game. The precise control and immediate feedback offered by the tangible interface seem to give players a greater sense of confidence and control, making the challenges feel more manageable.

> "The first version with pure gesture interaction would be more difficult, mainly due to issues with operational precision. It takes more time to get used to and can be challenging at first, which affects initial performance and confidence. In comparison, the second version with physical feedback allows me to control the tower more intuitively from the start, making it easier to pickup and master. (Participant #5)"

In context, participant #5 was more accustomed to using a keyboard and mouse for gaming. The tangible object was perceived as more similar to the keyboard and mouse due to their physical nature, making it easier to adapt. This point was confirmed by other participants as well. Regardless of their preferred interaction method in the past—whether it was keyboard and mouse, game controllers, touchscreen, or board games—they all found the tangible object to be more intuitive and easier to pickup. When it comes to winning, an interesting observation emerged. Two participants mentioned that using tangible objects seemed to increase their competitive spirit. They felt more excited and motivated, and were more determined to succeed in the game:

> "With gesture controls, I don't mind losing as much. But when using tangible objects, I feel like I have to win. I'm not sure why, but losing feels more frustrating, and I just have to try again until I win! (Participant #2)"

Through further discussion, we discovered that this increased desire to win might be linked to the tangible objects making the game feel less difficult. The precise control and immediate feedback provided by the tangible interface likely contributed to this perception, making players feel more capable and in control. This was also confirmed by responses to another interview question where each participant was asked to self-assess their skill level in the game. Most rated their skill level as average when using the gesture version, but felt above average with the tangible version. This sense of higher skill likely made them more driven to achieve success.

5 DISCUSSION

Our research aimed to investigate the role of tangible objects in shaping user experiences within AR environments. We conducted a study that investigated how gesture-based and tangible interactions influence player experiences in an AR tower defense game. We conducted a primarily qualitative study, combining observations and interviews with supplementary quantitative data from gameplay metrics, to explore how these two interaction modalities influence players' enjoyment, engagement, and overall experience.

The results indicated notable differences between the interaction modes. Specifically, a comparison of the key gameplay metrics showed that participants generally performed better across various metrics on the tangible interaction version, compared to the gesture-based interaction version. However, it should be noted that results from our quantitative analysis cannot be generalised to other studies, as our sample size was insufficient for making statistically significant claims. The semi-structured interviews revealed three main themes, related to enhanced immersion and realism, intuitive control and precision, and learning curve and challenge. To answer our research question, **How does the integration of tangible objects in an AR game influence player experiences when compared to a digital hand-gesture-based interface?**, we present our discussion on the three impacts of employing tangible interface on player experiences, based on the gameplay metrics and the themes we identified. The three impacts, listed in descending order of significance, are: (1) more intuitive control and precision; (2) enhanced immersion and realism; and (3) shorter learning curve and lower perceived challenge. Then, we present a list of design implications for employing tangible interfaces in AR, from the takeaways of our study.

5.1 Impact 1: More intuitive control and precision

Employing a tangible interface for AR tower defense game could provide a more intuitive control and precision. Our participants shared that the tangible interface offered more intuitive control and higher precision compared to the gesture-based interface, especially for the manipulation of the catapult. This could be attributed to participants' ability to make small adjustment with light movements or slight rotations with the tangible interface, whereas the gesture-based controls often caused larger, less precise changes due to the limitations of gesture recognition systems, which led to more adjustments. This can be supported by the results of our gameplay metrics, which showed that the tangible version resulted in fewer rotations and movements of the catapult (see Table 1). The lower frequency of shaking the tangible object also suggested a smoother, more seamless gameplay experience with fewer interruptions.

Through observations, we also noticed more active gameplay and higher degree of control with the tangible interface, where most of our participants continuously held the tangible object and adjusted the catapult's angle towards the enemies in real time. On the other hand, with the gesture-based version, our participants would only adjust the position and angle of the catapult when the enemies were about to leave the attack range. This is an interesting point worth exploring. This finding could be related to the work of Xu et al. [33], which demonstrated the positive impact of combining AR with physical objects on users' learning motivation and engagement, due to the rich digital affordances, intuitive tangible interactions, and the hybrid design.

From the interviews, our participants agreed that the tangible interface offered more intuitive control. The sense of control is indeed a subtle and hard-to-describe term, heavily influenced by participants' previous experiences with different control schemes like keyboards, mice, game controllers, and touchscreens. Despite these varied backgrounds, they unanimously highlighted the superior sense of control provided by the tangible object as a controller. They described this control as enjoyable and empowering, giving them a feeling of mastering the game's environment. This demonstrates the advantage of employing tangible interaction. Regarding precision, most of our participants believed that continuous control with the tangible object improved accuracy. However, we have to acknowledge there is still room for improvement in the recognition and tracking technique to enhance the objective precision of the tangible object.

5.2 Impact 2: Enhanced immersion and realism

Employing a tangible interface for AR tower defense game could enhance players' sense of immersion and realism to a certain extent. Many of our participants discussed how physically holding and manipulating an object made the virtual world feel more believable, whereas using gestures in the air felt empty, fake, and silly, making it hard to stay immersed. The heightened sense of immersion was often attributed to the tactile feedback provided by the tangible object, as our participants reported that the weight and solidity of the physical object gave them a strong sense of connection to the game world. Our results support previous research which showed that holding virtual objects with a lack of tactile stimuli would be unsatisfying for some people [16]. In addition, our results showed that the more intuitive control and precision of tangible interface also contributed to enhanced immersion and realism, because the fragmented feeling associated with gesture controls is reduced.

A few of our participants felt that the difference in immersion between the two interfaces was not very significant. In addition, one participant described how the tangible interface could be distracting at times, due to the need to manipulate a physical object that could sometimes draw their attention away from the game world. To further enhance immersion, we received feedback to utilise tangible objects that resemble the in-game buildings more closely, or vice versa. This feedback could be associated with findings of previous research, which suggested the importance of selecting a physical object that matches the shape and size of the virtual object as much as possible for the user's suspension of disbelief [10], while a mismatch would negatively affect the user's feeling of immersion and engagement [30]. In our study, the design of our tangible object was intentional, as we stuck to the concept of everyday objects, using simple shapes to explore if they influenced players' perception. One concern expressed by a participant illustrated why choosing simple shapes could be beneficial. Potential hassles could arise with the use of tangible objects, such as the tangible objects getting dirty, damaged, or even lost. Using simple shapes could minimise potential damages to or loss of smaller, more intricate, and fragile pieces, which would also be more difficult to clean. Future research may also seek to explore the potential for users to select their own tangible objects to be used in interactions.

Overall, while the tangible interface clearly enhanced immersion for most players, the relationship is nuanced. Despite the inherent advantage of tangible objects in enhancing immersion through their physical properties, the specific design and implementation of the tangible elements, as well as their consistency with the virtual world, seems also to play a crucial role in determining the impact on player experience.

5.3 Impact 3: Shorter learning curve and lower perceived challenge

A shorter learning curve was observed among players with the tangible interface version. Our participants cited the tactile feedback and more intuitive control of the tangible interface as the contributing factors to the ease with which they could learn to play the game. The precise control and immediate feedback associated with the use of tangible interface seemed to give players a greater sense of confidence and control, making the challenges feel more manageable. This finding is also supported by gameplay metrics, which showed that players achieved their first kill much faster in the tangible version (see Table 1). Additionally, the 100% completion rate further corroborates participants' feedback that the tangible interface reduced the perceived challenge of the game. Participants' ability to learn the tangible version more easily could be attributed to the embodied control via tangible objects and responsive feedback, which can provide users a clear understanding of their actions [9].

Interestingly, we observed that the tangible version also improved players' motivation to master the game and increased their desire to win, which were unexpected advantages. Further discussions with participant revealed that the greater desire to win could be linked to the tangible objects making the game feel less difficult. Due to the precise control and immediate feedback from the tangible interface, participants felt more capable and in control. This was demonstrated through a higher self-rated skill level with the tangible version (above average) compared to the gesture version (average), which likely made participants more driven to achieve success. However, it is important to make sure that players would still feel appropriately challenged. Thus, designing tangible interfaces requires careful balance to enhance the experience without introducing new frustrations.

5.4 Design Implications

This study's findings offer several valuable insights for designing similar tangible interfaces in AR games. These implications can guide tangible AR developers and designers in creating better user experiences.

- **Simplicity and Comfort:** Tangible interfaces should be designed with simplicity in mind. They do not necessarily need to be highly detailed or realistic representations of in-game objects. Instead, the focus should be on ensuring that the weight, shape, and grip of the tangible object feel comfortable and natural to the user. This simplicity can help players concentrate on the game itself rather than being distracted by the physical object.
- **Rich Physicality:** While keeping the design simple, it is important to leverage the unique affordances of tangible interfaces by providing rich physical feedback. This feedback may include diverse forms such as unique shapes, varied textures, or even vibrations. By engaging multiple sensory modalities, tangible interfaces can greatly enhance the sense of immersion and presence in the game world.

- **Intuitive Mapping:** The tangible interface should be intuitive and make sense to the player. It should have a clear and direct mapping to traditional game interactions, rather than attempting to completely overturn established conventions. Players should be able to understand and use the tangible object effortlessly based on their previous gaming experiences. This familiarity can reduce the learning curve and make the game more accessible.
- **Iterative Refinement:** Designing effective tangible interfaces requires a process of continuous iteration and refinement. Unlike 2D graphical user interfaces, which have well-established design patterns, tangible interfaces involve a wide range of design dimensions such as materials, size, shape, and other physical properties. Designers must carefully balance these attributes, testing different configurations to find the optimal combination that enhances gameplay without hindering usability.
- **Affordance-Driven Design:** A key consideration in designing such interfaces is to provide ample opportunities for meaningful interaction by fully leveraging the physical properties of the objects. This requires a deep understanding of the affordances offered by various physical materials and mechanisms, such as magnets, springs, and cleverly designed mechanical structures. By thoughtfully incorporating these elements, designers can create tangible interfaces that invite exploration and discovery, naturally guiding users towards the intended interactions. The goal is to design tangible objects that not only complement the digital experience but also extend it in intuitive and engaging ways.
- **Contextual Integration:** Tangible interfaces should be designed to integrate seamlessly with the specific context and requirements of the application. In the case of the AR tower defense game in this study, we conducted an extensive exploration of existing interaction paradigms within the genre. However, we found that directly applying tangible objects to traditional tower defense mechanics posed significant challenges. As a result, we made the decision to substantially modify the conventional interaction model, arriving at the current design that revolves around physically manipulating a catapult. Designers should carefully consider how the tangible interface can be tailored to support and enhance the central mechanics and themes of their specific application, even if it requires making trade-offs or deviating from established conventions.

5.5 Limitations and Future Directions

While this study provides valuable insights into the effects of tangible interaction on player experience in AR games, it is important to acknowledge its limitations and identify potential avenues for future research.

5.5.1 Sample Size and Diversity. One limitation of this study is the relatively small sample size (n=10) and limited diversity of participants. The exploratory nature of the study and time constraints contributed to this limitation. As a result, the small sample size prevented us from performing robust statistical analyses on the quantitative data. Future research should aim to recruit a larger and more diverse sample to improve generalisability and enable more effective use of well-known surveys, such as the PENS [28] or PXI [1], to strengthen the validity of the findings.

5.5.2 Different Types of Tangible Interface. This study evaluated only one specific type of tangible interface. As a result, design implications derived from this research may not be directly applicable to other tangible interfaces. Future research should explore a variety of tangible interfaces to determine whether the observed impacts hold true.

5.5.3 Tangible Object Recognition. The recognition of tangible objects in this study relied on traditional computer vision algorithms for marker detection, which restricted the design of the physical objects to some extent. One noticeable issue was the placement of the marker on the top of the cube, leading to a height difference between the detected marker position and the actual cube position. This discrepancy resulted in some misalignment of the overlaid AR content, particularly when the cube was further from the camera center. Exploring deep learning-based detection methods could potentially overcome these limitations and enable more diverse and complex tangible object designs, such as the initially proposed flippable-top cube.

5.5.4 Game Mechanics and Variety. Due to time constraints, the implemented game mechanics, modes, and tower types were relatively limited compared to the initial proposals. The inclusion of more diverse tower types and abilities could have revealed additional nuances in the differences between the two interaction modes. Future studies should consider expanding the game design to explore a wider range of mechanics and assess their impact on player experience.

5.5.5 Multiplayer and Social Aspects. This study focused on a single-player AR game experience. However, tangible AR has the potential to enhance social interactions and collaboration in multiplayer settings, particularly in augmenting traditional board games. Future research could investigate the social aspects of tangible AR games and how they influence player engagement, communication, and overall experience.

5.5.6 Tangible AR for Rehabilitation. The physical manipulation involved in tangible AR interactions could potentially be applied to hand rehabilitation exercises. Future studies could explore the therapeutic benefits of tangible AR games in the context of physical therapy and rehabilitation, assessing their effectiveness in improving motor function, motivation, and adherence to treatment programs.

5.5.7 Long-term Effects and Skill Transfer. This study examined player experience in a single gaming session. Future research could investigate the long-term effects of tangible AR interaction on player engagement, learning, and skill acquisition. Additionally, exploring the transfer of skills developed through tangible AR gaming to real-world tasks or other domains could provide valuable insights into the broader implications of this interaction modality.

6 CONCLUSIONS

In this paper, we presented a study that investigated the effects of tangible and gesture-based interaction on player experience in an AR tower defense game. We designed and developed two versions of the game: one that used hand gestures for interaction and another that employed a tangible interface with a 3D-printed cube and attachable pieces. We conducted a qualitative study using observations and interviews as the primary methods, with supplementary quantitative data from gameplay metrics, to explore how these two interaction modalities influence players' enjoyment, engagement, and overall experience. The qualitative analysis of observations and interviews suggests that tangible interfaces may contribute to positive experiential outcomes by providing immediate tactile feedback, natural mapping to in-game actions, and a sense of control and direct manipulation. To enhance player experience with tangible AR interfaces, we discussed several design implications based on our findings, emphasising the importance of simplicity, comfort, rich physicality, intuitive mapping, iterative refinement, affordance-driven design, and contextual integration.

Our study demonstrates the potential and practical value of tangible interfaces for enhancing player experience and engagement in AR gaming. Within the HCI community, the results offer insights into designing tangible interfaces that create compelling and immersive AR experiences, thereby promoting their wider application in the gaming industry. Additionally, the design implications derived from our research provide practical guidance for game designers and researchers aiming to creating novel tangible interfaces for AR games. These findings may also have implications for the application of tangible interaction across various fields, such as education, training, and rehabilitation. Future work should include larger and more diverse sample sizes, exploring a variety of tangible interfaces, examining tangible object recognition, investigating additional game mechanics and elements, considering other use cases, and assessing the long-term effects of tangible AR interaction.

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Received 26 June 2024