Key dimensions in IoT-enabled serious AR games for awareness of indoor air quality and healthy behavior reinforcement: an exploratory case study*

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Abstract
This study explores the design and development of serious games using augmented reality (AR) technologies integrated with IoT sensors. The aim is to raise student awareness of air quality in their study environments. The study employed qualitative data gathered from three iterations of game implementations with thematic analysis. Results were classified into four key dimensions: IoT integration and data management, game design and mechanics, user experience and engagement, and educational impact and outcomes. Findings indicate that real-time environmental data can reinforce IAQ awareness and prompt healthier decision-making within a game context, although sustaining user engagement and overcoming technical barriers remain challenges. Moreover, incorporating refined game design elements such as improved feedback loops may enhance both educational impact and motivational appeal.

Keywords
serious game, IoT, AR, IoTeSG, pervasive gaming, game design, game development

1. Introduction

Indoor air quality (IAQ) in educational institutions has garnered increasing attention due to its direct influence on student performance and well-being. Classrooms' indoor environmental conditions have been recognized to affect academic achievement among students and teachers in higher education, highlighting the importance of adequate ventilation, temperature control, and air filtration measures [1]. Various factors have been identified in classrooms such as CO_2 levels and pollutant concentrations that directly impact student academic performance and overall health [2].

People in both developing and developed countries spend an estimated 80–90% of their time indoors. Although HVAC systems aim to maintain indoor environmental quality (IEQ), they are not always effective, and health organizations' guidelines for IEQ are often only voluntary. Various pollutants from building materials and occupants contribute to poor IAQ, which can lead to numerous negative health outcomes. For instance, insufficient air circulation can facilitate the spread of infectious diseases [3].

Studies on the IEQ of university classrooms revealed that poor indoor air quality, which is characterized by high levels of CO_2, inadequate ventilation, and other environmental factors, has a negative impact on students' concentration, productivity, and overall health. The students are at greater risk because of the long hours they spend in these environments. As a result, improving the IAQ in classrooms is critical for improving student wellbeing and academic performance [4].

The Internet of Things (IoT) has been developed and implemented over the last decade for numerous use cases ranging from industry use and many ways it has become a cornerstone of our digital society [5]. The concept of IoT is described as a means of creating a novel form of pervasive

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technology by incorporating radio-frequency identification and other sensors into ordinary things [6]. It has been incorporated into many public and private spaces in the form of smart sensors that can measure various things, such as movement, light, and air quality [7].

Serious games are digital or mixed-reality experiences that engage players through story and gameplay to inform or influence [8]. They have been emphasized having a useful purpose, otherwise, all virtual games could be considered educational by default [9].

This research explores the potential of IoT-enabled augmented reality (AR) serious games to raise student awareness of IAQ and promote healthier behaviors. By integrating real-time IoT sensor data with AR, we developed the *Legend of Alumnus*, an interactive game that merges virtual and physical environments to educate students on the impact of IAQ on their health and behavior. The primary objective is to design and assess the effectiveness of such games in fostering IAQ awareness and encouraging behavioral change by motivating students to navigate their campus toward locations with better air quality. This integration creates an educational experience that extends beyond the digital screen, reinforcing the importance of IAQ in everyday decisions.

To guide this investigation, we address the following research questions (RQs):

- **RQ1:** How can real-time IAQ sensor data be effectively integrated within an AR game to enhance students' awareness of indoor air quality?
- **RQ2:** Which game design features and user experience factors most significantly influence student engagement and healthy behavior reinforcement in an IoT-enabled AR game aimed at IAQ awareness?

2. Background

The scientific community recognizes the potential of serious games in healthcare, particularly when integrated with IoT-enabled monitoring devices to promote healthy behaviors like physical exercise. Personalization within these games enhances their effectiveness, with engagement levels reflecting the success of the healthy behaviors encouraged by the IoT-enabled serious games (IoTeSGs) [10-12].

[13] explored an IoT-enabled AR exergame that combines virtual and real-world tasks while leveraging biometric data from wearables and sensors for game adjustments. Although participants reported improved physical activity and health metrics, the study highlighted the need for more streamlined interfaces in complex environments. In parallel, [14]'s investigation of pervasive mixed-reality games underscores the importance of studying how virtual and physical elements intersect in player experiences, recommending robust methodologies to better understand and validate game design choices in mixed-reality contexts. [15] examined an AR-based serious game for air quality awareness, using avatars that change appearance based on real-time data. User feedback noted the game's educational and entertainment value but suggested design improvements for simplicity and intuitiveness. The study underscores AR and IoT as effective in representing data interactively, though immersive aspects need further exploration.

[16] proposed a conceptual model for user engagement in mobile-based AR games identifying clear goals, satisfaction, challenge, focused attention, perceived usability, interaction, social elements, and mixed fantasy as key drivers of user engagement, aligning with [17], who stress the importance of well-defined objectives, rewards, and regular feedback in fostering intrinsic motivation, while appealing aesthetics can evoke emotional engagement and encourage players to ignore external distractions. Additionally, studies show that familiarity with real-world settings can reduce fatigue in location-based AR games, while newcomers often experience higher immersion, sometimes even struggling to reorient to reality [18]. AR features in location-based games have been found often undervalued due to slow responsiveness. However, integrating Points of Interest (PoI) with real-world context or history makes gameplay more meaningful and motivating, while representing real-world objects on in-game maps effectively bridges the gap

between physical and virtual environments [19]. Brand appeal, social interaction, and progression systems (e.g., collecting items, leveling up) can sustain long-term interest in AR games like Pokémon GO; conversely, technical issues and repetitive progression lead to disengagement [20]. From a technical standpoint, IoT-enabled serious games require robust architectures, security measures, standardized data management, hardware considerations, and reliable connectivity [21]. For instance, MQTT can efficiently transfer sensor data, but data structure consistency and authentication are essential for scalability.

3. Methodology

This study adopts an exploratory case study design as outlined by Yin [22] to investigate how an IoT-enabled serious game can raise student awareness of indoor air quality. Exploratory case studies are especially suitable for examining novel or not yet fully understood phenomena, which in this case involves integrating real-time IoT sensor data with AR mechanics. Such a design offers flexibility in uncovering emergent patterns and evolving relationships among gameplay, sensor data, and user engagement, particularly when the boundaries between the research context and the phenomenon are unclear.

3.1. Iterative development process

This section presents the Legend of Alumnus game, its three iterations, their game design, why certain design aspects or principles were selected, and how these were implemented in conjunction with the IAQ sensor data. The game utilizes both AR game and IoTeSG design paradigms. The purpose of the game is to explore new ways to utilize IoT sensors so they can purposefully affect the gameplay mechanics. The project spanned from 2022 to 2024, over three iterations, with separate student groups from the Research & Development project course in Information Processing Science at the University of Oulu. Throughout the process, the researcher and product owner guided the design and development to ensure that the outcomes were meaningful for research into IoT sensor and AR usage in games.

The initial concept of the game, presented to the student groups, involved creating a game based on university mythology, incorporating location-based gameplay and AR, while leveraging the smart campus IAQ sensor network that had been implemented throughout the campus. Although the concept and certain project requirements were part of the assignment, the student groups were given the freedom to design the game and its mechanics as they saw fit.

The game development followed an iterative design process across three distinct versions. The iterations are summarized in Table 1, which provides an overview of each version's platform, genre, game loop, and the integration of IoT sensor data and location-based mechanics. Figure 1 presents the user interfaces of each iteration. Each iteration focused on improving specific aspects of the game, such as IoT sensor data integration, location-based mechanics, and gameplay progression.

3.1.1. First iteration

The initial prototype of Legend of Alumnus was developed as a location-based AR action role-playing game (RPG) for Android. Players navigated the campus physically, encountering ghosts spawning near IAQ sensor locations. Due to integration challenges, historical IAQ data was used, with ghost spawn rates linked to local IAQ levels. The game featured a 3D campus map, and ghost encounters led to AR battles where players shot ghosts to reduce their health until capture. An inventory provided capture aids, and a ghost database allowed players to collect and track different ghost types. In this first iteration, testing was conducted exclusively within the development team and the project's customer company. The primary focus was on ensuring the game's basic functionality and testing the initial integration of historical air quality data with the game mechanics. At this stage, the emphasis was placed on identifying technical challenges, resolving gameplay issues, and improving the integration of IAQ data. No formal usability tests were conducted during this phase, as the game was still in an early prototype stage.

Table 1
Iterative development of the Legend of Alumnus game.

Iteration	Platform	Genre	Game loop and progression	IoT data integration with gameplay mechanics	Location integration
1st	Android	Action role-playing, location-based AR game	The player navigates the campus encounters ghosts in the game and fights them.	Historical data was used. Spawn count is proportional to the IAQ level.	Ghost spawns in a random location near the player and moves closer until it attacks and causes damage.
2nd	PC	RPG with turn-based combat	Main loop: players navigate and encounter ghosts while collecting items, including keys, to progress. Subsidiary loop: they earn rewards and XP points to level up.	Enemy power level increased with sensor data (CO_2, motion, temp, light).	No location integration.
3rd	Android	Location-based AR game, Idle game	Main loop: players navigate the campus physically to place virtual pets. Subsidiary loops: the virtual pet accumulate points and evolve with better IAQ.	Point accumulation is proportional to IAQ of the placed location of the virtual pet.	Player location tracked and mapped within the game world. The player needs to place the virtual pet near their location.

3.1.2. Second iteration

The second prototype took a different approach in its game design. While the first prototype concentrated on AR-style gameplay with location-based mechanics, the second iteration presented a classic RPG design and gameplay, where smart campus sensors influenced the strength of enemies appearing on the game map. There was no player location integration, and the player navigated the pixel-style university map using a keyboard and mouse on PC. In this iteration, the game loop consisted of the player navigating the game world, following a storyline, and collecting items, such as keys, to progress. When encountering ghosts, a turn-based battle scene would start, where the player had options to attack, defend, heal, or wait. Additionally, the game included a subsidiary loop in which the player earned rewards and experience points (XP) to level up.

The second iteration of the game introduced a structured evaluation, applying a heuristic evaluation framework based on [23]'s Heuristic Evaluation of Playability. This internal assessment with five test users focused on playability and usability, evaluating the interface, navigation, and gameplay mechanics. Key heuristics included ease of use, player motivation, rule clarity, and effective integration of IoT sensor data. Conducted by the development team, the evaluation aimed to identify usability and gameplay issues, refining mechanics, UI, and the use of real-time IoT data, such as adjusting enemy strength based on environmental factors like CO_2, motion, temperature, and light.

3.1.3. Third iteration

The third iteration took a more serious turn; while the game design of the two first iterations concentrated on creating a fun and engaging experience of playing a game revolving around the campus, in third iteration, the IAQ on campus and how it affects the health of students was in center of attention. The core design aimed to encourage students to avoid areas with poor air quality, particularly where CO_2 levels exceeded a certain threshold.

The game genre remained location-based AR game, but it incorporated strong design elements from contemporary idle games. The main game loop involved the player navigating the campus and selecting study locations based on IAQ information provided by the game. Players were tasked with placing a virtual pet-style spirit companion in areas with good air quality. To nurture their spirit companion, the player had to periodically relocate the spirit to maintain its health in good IAQ zones. If left in a bad IAQ area for too long, the spirit would become sick, reducing the player's ability to earn Intellectual Points (XP).

While the player was idle, they could occasionally feed the spirit with resources collected from specific locations on campus. In addition, players were periodically awarded with spirit evolutions, adding another layer of gameplay complexity through a secondary loop.

Figure 1: User interface designs from each iteration of the game.

In this final iteration usability testing was conducted using an Android test APK, involving both internal team members (e.g., four student developers) and external volunteers (four test users) with diverse backgrounds in technology and gaming. Following best practices in usability research by [24], each participant was guided through six tasks: (1) navigating to a specified location using the in-game map, (2) placing the spirit in high-IAQ areas, (3) evolving the spirit companion, (4) collecting and feeding resources, (5) responding to high CO_2 alerts, and (6) freely exploring the AR environment thereby evaluating key game mechanics, real-time IoT sensor data integration, and educational effectiveness. After completing these tasks, participants filled out a questionnaire assessing navigation clarity, system performance, perceived educational value, and overall engagement.

3.2. Data collection

At the end of each iteration, developer experiences were systematically collected and documented through various project artifacts and reports. These included game design documents, expertise reports, project plans, steering group meeting minutes, mid- and final reports, project portfolios, seminar papers, PowerPoint presentations, Unity game project scripts, communiques between the project team and the customer, game evaluation reports, and the game builds for both Android and Windows platforms. This comprehensive set of documentation captured the development process, challenges encountered, decisions made, and the outcomes of each iteration. Alongside user feedback from the testing phases, these materials served as the primary data for analysis.

3.3. Analysis

The data collected from these artifacts were analyzed using Braun and Clarke's thematic analysis method [25], which provided a structured approach to identifying patterns or themes across the iterations. As outlined in Table 2, thematic analysis was conducted in five steps to ensure a thorough examination of the design and development, as well as the educational impact of the game.

The first phase was a thorough examination of all the relevant documentation and artifacts of the three iterations of the project. Straight from the data, inductive reasoning was used to extract evidence patterns and insights.

The evidence was then categorized under key aspects of game development. To ensure that the coding was limited to evidence that contributed to unique insights, this stage required filtering out common knowledge components to concentrate on material that could yield new understandings. Abductive reasoning was used.

Then, similar bits of data were grouped into coherent categories to uncover first-order themes. Inductive reasoning was used to combine cohesive themes from related evidence. After that, second-order themes and aggregate dimensions were created by further abstracting and synthesizing first-order themes for structured and comprehensive analysis of the qualitative data. In this stage, inductive reasoning was still used.

In the final step, the underlying core causes and effects of each aggregate dimension were investigated. This step involved connecting the aggregate dimensions with reasoning and evidence from literature. The goal was to confirm the findings by connecting the aggregate dimensions to existing theoretical frameworks, utilizing abductive reasoning to ensure robustness.

4. Results

This chapter presents the key results of the thematic analysis, which are organized into four primary aggregate dimensions: IoT integration and data management, game design and mechanics, user experience and engagement, and educational impact and outcomes. Figure 2 presents the key thematic dimensions identified in the analysis.

Table 2
Steps and methodological approaches in thematic analysis for iterative game development.

Step	Description	Analysis focus	Methodological approach
1	Analyzing each documented evidence produced in each iteration	Identification of data sources with empirical evidence for the project objectives	Inductive
2	Classification of the evidence under all the key aspects of game development	Filter common knowledge elements to ensure coding focuses on evidence that can generate new understandings	Abductive
3	Identify first-order themes	Combine related evidence into cohesive themes	Inductive
4	Identify second-order themes and aggregate dimensions	Further abstraction and synthesis of the first-order themes for structured and comprehensive analysis of qualitative data	Inductive
5	Analyzing core causes and effects of each aggregate dimension	Connect aggregate dimensions with reasoning and evidence from the literature to confirm the findings	Abductive reasoning

4.1. IoT integration and data management

Effective integration and management of IoT sensor data played a crucial role in the game's development and functionality. The reliability and accessibility of data were central to ensuring that the game could dynamically respond to real-world conditions, and several critical factors were identified in the process.

Data accessibility and reliability emerged as one of the key components for successful implementation. The use of persistent flags within the MQTT broker was instrumental in maintaining data reliability, particularly when sensor updates were infrequent. These flags allowed the system to preserve the most recent data, ensuring that even when the sensors weren't continuously sending updates, the game could still access reliable, up-to-date information. The inclusion of these persistent flags mitigated potential data losses and allowed for smoother game performance

Another key finding in this area involved the structure of the data itself. Initially, all devices were publishing sensor data under a single topic within the MQTT broker, which created significant bottlenecks during game initialization. The lack of a structured, atomized approach meant that the system had to process a large volume of irrelevant data, causing delays in loading the game levels. This inefficiency was addressed by restructuring the MQTT broker to publish data in separate topics, allowing the game to initialize much faster. Furthermore, atomizing the data structure, combined with persistent flags, proved to be highly effective in enhancing data management.

Despite these improvements, real-time data access remained a challenging aspect of the development process. The MQTT broker lacked the capability to specifically target the most relevant sensors, which presented difficulties when the game needed to fetch real-time data for dynamic game mechanics. This issue was particularly noticeable during the third iteration, where the game struggled to fetch only the latest sensor readings. Consequently, the project team implemented a solution that relied on historical data retrieved through the smart campus REST API to expedite the initialization process. While this workaround helped resolve initialization delays, it also highlighted the limitations of the MQTT broker's real-time data handling capabilities.

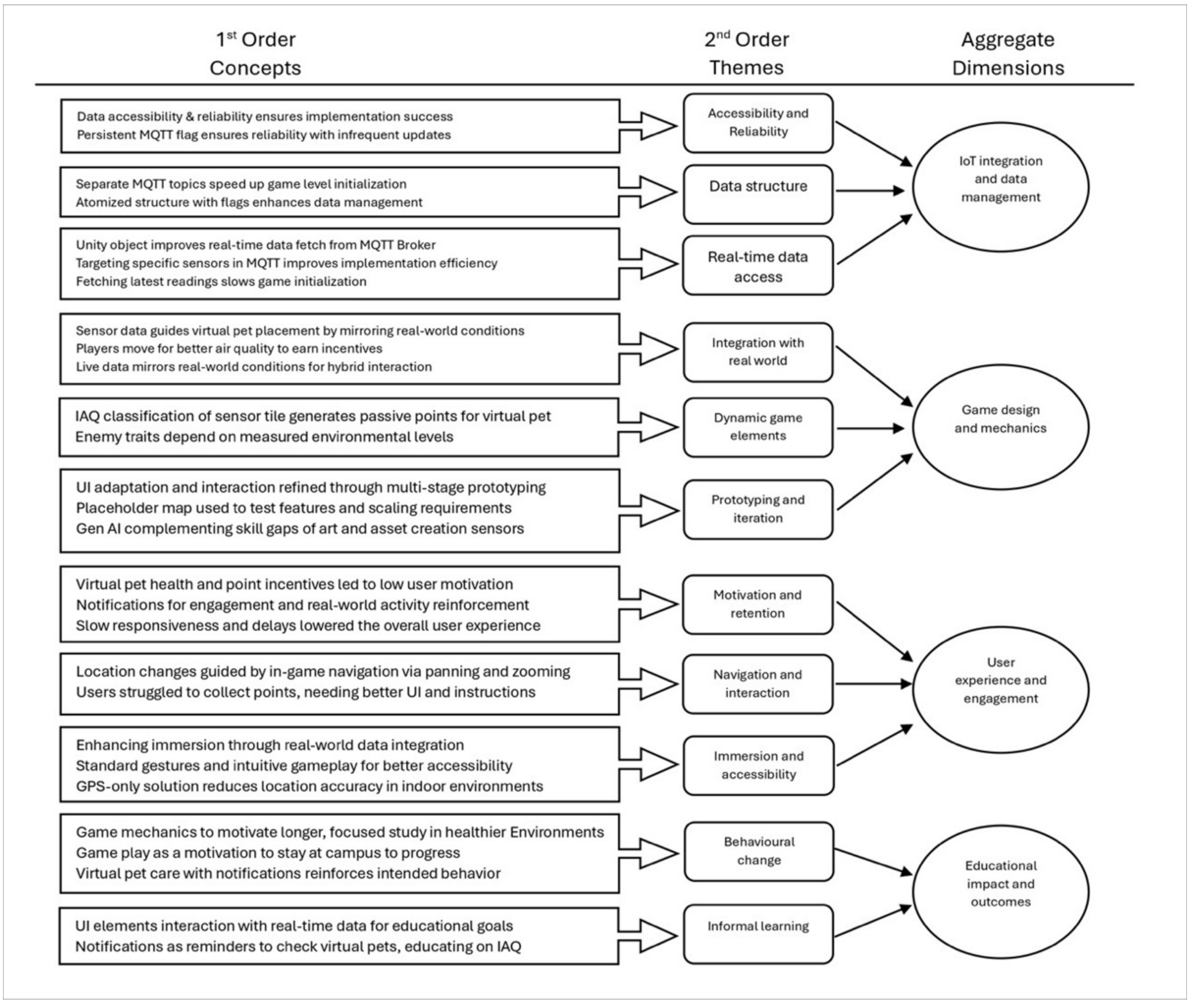

Figure 2: Systematic data structure from thematic analysis

The use of Unity game objects to fetch real-time data directly from the MQTT broker further optimized the gameplay experience. The Unity game objects were specifically designed to handle the real-time sensor data that influenced various aspects of the game, such as updating enemy power levels and affecting quest outcomes. By integrating live environmental data into the game mechanics, the game could mirror real-world conditions in real time, creating a more immersive and responsive experience for the players. However, the inability to consistently retrieve only the latest sensor readings meant that in some cases, game initialization was slower than desired, particularly when dealing with a large number of sensors.

4.2. Game design and mechanics

The design and mechanics of the game evolved through iterations, with a consistent focus on integrating real-world data into the virtual environment, aiming to enhance player engagement, and refining gameplay elements based on sensor inputs. Each aspect of the game's design was shaped by the need to mirror real-world conditions, allowing players to interact with both their physical and virtual surroundings.

One of the defining features of the game was its use of real-world air quality data to influence in-game mechanics. Throughout the iterations, players were required to physically move within the game's environment to seek out areas with better air quality, which would provide in-game incentives. This was particularly evident in the third iteration, where players had to place virtual pets in locations with favorable air quality to ensure their pets thrived. The University of Oulu campus was recreated virtually, and the game's mechanics were designed to reflect live sensor data from this real-world location.

This approach was not just about providing players with information but about integrating it seamlessly into the gameplay. The player's real-world position was mirrored within the virtual world, ensuring that decisions made in the game were influenced by real-time conditions. For example, players could not place their virtual pets in locations that were far from their actual physical position, further emphasizing the link between the virtual and physical worlds. Sensor data thus became a critical gameplay element, informing where pets could be placed and how they interacted with the environment.

Another key feature of the game was the use of dynamic game elements, driven by real-time air quality data. The game used the classification of air quality, particularly CO_2 levels, to generate passive points for the player's virtual pets. Each sensor in the real world corresponded to a specific area in the virtual game world, and the CO_2 levels from these sensors determined how the environment within that area would behave. For instance, areas with poor air quality would result in fewer rewards for the player, while areas with better air quality would provide additional points and benefits. This dynamic interaction between real-world environmental data and in-game mechanics added complexity to the gameplay, as players were encouraged to make strategic decisions based on real-time data.

In addition to influencing passive point generation, environmental data also shaped the behavior and characteristics of in-game enemies. The number, size, and power levels of enemies in the game were directly linked to the environmental data captured by specific sensors. In the first and second iterations, the strength of enemies and their spawning rates were tied to air quality levels, with tougher enemies appearing in areas with poorer environmental conditions. This added a layer of challenge to the game, as players had to factor in real-world environmental factors when planning their movements and strategies.

The iterative design process allowed for continuous refinement of the game's user interface (UI) and interaction elements. The development team adopted a multi-stage prototyping approach, starting with low-fidelity sketches and wireframes to test basic functionalities. These early designs provided a foundation for high-fidelity prototypes that were later developed in tools such as Figma, which enabled the team to fine-tune the aesthetic and functional aspects of the game.

A key focus during this iterative process was ensuring that the game's UI could adapt flexibly to meet both aesthetic and functional demands. By working through multiple stages of prototyping, the team was able to refine the user experience, improving both the visual appeal and the usability of the game. The placeholders used in early iterations allowed for the testing of features and scaling requirements, ensuring that the final design could handle the complex interactions between real-world data and virtual game elements.

Another important aspect of the iteration process was the use of generative AI to fill gaps in art and asset creation. The team faced challenges in creating game assets that fit the selected themes due to limited resources and skills in art and design. To overcome this, they employed generative AI, which allowed them to produce better quality assets. While the lack of existing protocols or guidelines for using generative AI in game development was an initial barrier, the approach proved to be successful for the project outcomes in the second iteration where generative AI was used.

4.3. User experience and engagement

User experience and engagement in the game were evaluated through testing and feedback in the third iteration. Key insights revealed issues with player motivation, navigation, interaction, immersion, and accessibility. A primary challenge was the low engagement with the game's environmental goals. The virtual pet system, involving pet care and point rewards, lacked strong incentives to keep players interested. The pets' health and points linked to air quality were not compelling enough, leading to reduced player motivation to engage with environmental aspects like air quality monitoring or real-world actions based on in-game data.

The usability testing also highlighted several issues with navigation and interaction within the game. Although the app's basic navigation was generally perceived as simple, users expressed a need for clearer and more intuitive navigational aids. For example, participants found it difficult to distinguish player pins and virtual pet locations on the map, which affected their ability to interact smoothly with the game world. This confusion indicated that the UI needed further refinement, particularly in terms of its icons and map elements.

Furthermore, some users struggled to complete tasks related to collecting points or interacting with specific game features, pointing to gaps in the clarity of the game's instructions. The need for more explicit, in-game guidance was evident, as players often found themselves uncertain about the steps required to progress or complete certain tasks. These findings suggested that better UI enhancements and clearer instructions were crucial to improving the overall player experience.

The game's design prioritized immersion and accessibility, using real-world data integration to boost player engagement. Real-time interactions between the virtual and physical worlds created a strong immersive effect, helping players feel connected to both. This feature, which linked real-time data to in-game outcomes, was well-received, supporting the game's educational and environmental goals. However, some technical issues slightly impacted the overall immersion.

One significant issue was the game's use of GPS for indoor location tracking, which resulted in inaccurate measurements. The initial implementation of the location service API in the Unity engine defaulted to GPS, which is generally ill-suited for indoor environments due to non-line-of-sight (NLOS) conditions. These conditions led to inaccurate tracking, further compounded by the Unity API's insufficient documentation on indoor location tracking. Since the gameplay environment was entirely indoors, these challenges had a considerable impact on the user experience.

To address these issues, the development team implemented network-based localization techniques, which significantly improved the accuracy of indoor tracking. This solution helped bring the location tracking to an acceptable level, making the game more responsive and enhancing the immersive experience for the players. In addition, the game's use of standard gestures, such as pinching and zooming, contributed to a more intuitive gameplay experience, ensuring that players could interact with the virtual environment in a familiar and accessible manner.

4.4. Educational impact and outcomes

The game's design was aiming to encourage healthier behaviors and provide informal learning opportunities related to indoor air quality.

One of the main goals of the game was to promote behavioral change by motivating players to spend more time in environments with better air quality, thereby encouraging healthier habits. Players were required to be physically present on campus to progress in the game (in first and third iterations), tying real-world movement and location to game rewards. This requirement was seen as motivating to stay in campus for longer periods and encouraging to stay in areas with better IAQ.

The use of virtual pets in the third iteration served as a key mechanism for reinforcing these behaviors. Players were encouraged to place their virtual pets in locations with good IAQ, as poor air quality would negatively affect the pets' health, causing them to devolve. This negative reinforcement mirrored real-world consequences and pushed players to seek out healthier environments, thus integrating the educational goal of raising awareness about the importance of IAQ. The design also included notifications as reminders to take breaks or move to better air quality locations.

The effectiveness of these behavioral cues was enhanced by the lack of a need for continuous active tracking. Players did not need to monitor the game constantly; rather, periodic interactions with their virtual pets acted as brief study breaks and moments to reflect on the indoor environment, subtly encouraging behavioral change without overwhelming the player.

In addition to promoting behavioral change, the game fostered informal learning about indoor air quality through its use of real-time data and interactive UI elements. The game's interface displayed IAQ information in a way that was directly linked to the player's environment, allowing them to see how air quality affected their virtual pets and overall game progression. User feedback from the questionnaire, however, revealed mixed understanding of the app's purpose and mechanics, suggesting a gap in clear communication. Moreover, motivation to engage with the game's environmental goals was generally low, underscoring a need for better incentives and improved feedback loop.

The inclusion of notifications contributed to the informal learning process. Reminders to check on virtual pets after closing the app served as gentle prompts, encouraging players to reflect on air quality and its importance. These notifications were designed to trigger with a delay, ensuring that players remained engaged with the game's educational goals even during periods of inactivity. The periodic check-ins with virtual pets acted as a tool for reinforcing the knowledge that better air quality leads to more positive in-game outcomes, indirectly teaching players the value of maintaining healthier environments in real life. However, malfunctioning CO_2-level alerts and other notifications, which are crucial for enhancing gameplay engagement and the educational use of real-time data, were significant issues, with participants expressing a desire for a fully functional notification system to better support both gameplay and educational objectives.

5. Discussion

The study contributes to the field of IoT-enabled serious AR game development in four key aspects: IoT integration and data management, game design and mechanics, user experience and engagement, and educational impacts and outcomes.

The IoT integration and data management aspects include accessibility and reliability, data structure, and real-time data access. Data accessibility and reliability were critical, with persistent flags in MQTT broker publish events enhancing reliability when updates were infrequent. Efficient data management required an atomized data structure and separate MQTT server topics for device data, enabling faster game level initialization. [21] emphasized the importance of data preprocessing and normalization for uniformity, a finding our study extends by detailing practical implementations. It has been pointed out that IoT-enabled serious gaming with AR is an enhanced interactive technique to present digital data in the real world [15]. The study explored practical avenues for achieving this with utilization of game objects for fetching the real-time data from broker, capability of targeting individual sensors in MQTT broker and capability to fetch only the latest sensor reading. These aspects contribute to reflecting real world conditions via game mechanics operated in real time.

The game design and mechanics include three core aspects: real-world integration, dynamic game elements, and prototyping with iteration. Real-world integration involves three key elements: sensor data reflecting real-world conditions to inform and impact the virtual environment, live data integration to create a mirrored, hybrid interaction space, and game rules based on player proximity, allowing interaction with real-world locations. Integrating real-world elements into AR objects creates a unique experience in AR gaming, though seamlessly blending virtual and physical content remains challenging [16]. These insights offer practical solutions, enhancing immersion and user experience by fostering familiarity and reducing cognitive load [18]. Dynamic game elements focus on using environmental sensor data to shape incentives and challenges based on each location's conditions. Successful prototyping and iteration were impacted by three factors: flexible UI adaptation for aesthetic and functional needs across prototyping stages, smooth transitions between fidelity levels for in-depth exploration of interactive elements and using placeholder maps to test and scale features. Generative AI supported asset creation, addressing skill gaps in the development team. Aesthetic design improved navigation and enhanced emotional engagement through visual and audio elements [17]. These findings support a multi-fidelity prototyping approach and the integration of generative AI in design.

Three main components were identified in user experience and engagement: motivation and retention, navigation and interaction, and immersion and accessibility. Findings showed that key factors for motivation and retention included faster game responsiveness and well-designed incentives, aligning with literature linking engagement to progression and diverse rewards [20]. Studies also suggest users devalue AR when responsiveness lags [19]. Notifications reinforced real-world activities, aiding player retention. Effective navigation involved panning, zooming, and clear in-game instructions, while immersion and accessibility benefited from real-world data integration, standard gestures, intuitive gameplay, and accurate location tracking, with GPS proving ineffective indoors.

The educational impact of IoT-enabled serious AR games was observed in two areas: behavioral change and informal learning. Real-time data interactions through notifications and UI elements supported informal learning about indoor environmental conditions, aligning with research showing that AR-based avatars enhance educational outcomes by combining learning with entertainment [15]. Studies also highlight the effectiveness of IoT-enabled games in promoting healthy behaviors by monitoring environmental and user data [12, 13]. The game mechanics used notifications to reinforce healthy behavior and encourage users to be present in specific locations as intended by design.

However, usability tests of the third iteration identified technical and pedagogical challenges. Participants found navigation manageable but requested clearer map icons and instructions. Technical issues, such as slow responsiveness, hindered immersion and sensor data integration, reducing both engagement and IAQ awareness. Additionally, the game emphasized recognizing poor air quality over providing actionable steps, highlighting the need for more behavior-oriented design elements.

6. Conclusion

This study explored the design and development of IoT-enabled serious games using AR technologies to raise student awareness of IAQ and promote healthy behaviors. Utilizing data from three iterative implementations and applying Braun and Clarke's thematic analysis [25], four key dimensions were identified: IoT integration and data management, game design and mechanics, user experience and engagement, and educational impact and outcomes. The findings demonstrate the potential of such games to drive behavioral change and enhance user engagement while highlighting the necessity of overcoming technical barriers and refining educational content. By effectively integrating IoT data with AR mechanics, this study offers practical guidance for designing and implementing gamified applications. It underscores the importance of robust data management, dynamic game design, and user-centered interactions in creating immersive educational experiences that raise awareness and encourage meaningful behavior change in real-world environments. These contributions advance both theoretical understanding and practical applications in the field of IoT-enabled serious games.

7. Limitations and future work

One significant limitation of this project was the initial lack of clarity in objectives. The original idea was simply to create a game that incorporated real-life data into its game mechanics, without a well-defined long-term vision or rigorous methodology. As the project progressed, the concept was gradually refined through iterative development, but the process lacked a structured approach. Consequently, the collection and categorization of research data were inconsistent. Future research must create explicit theoretical and practical foundations for the usage of IoT sensors in games.

Integrating established game design principles with IoT sensor technology will result in a more structured and focused approach to IoT-enabled serious game design and development. This will ensure that future initiatives accomplish their aims and provide vital insights on how to effectively integrate IoT technology into educational and environmental awareness games. The practical application of generative AI throughout various stages of the game development process represents a promising area for future research. This technology empowers developers with limited resources or skills to design impactful games more efficiently and creatively.

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