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Article

Forest Classroom: A Case Study of Educational Augmented Reality Design to Facilitate Classroom Engagement

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Abstract: The transition from kindergarten to primary school involves preparing students for a more structured classroom-based learning environment, which is typically different from the play-based model in kindergartens. Building on the Forest Room concept, which connects restless and disengaged students to nature as a calming medium, this case study describes the design of a combined storybook and augmented reality application to provide a literacy primer that integrates this concept. The design case study is presented relative to three frameworks that review the support for educational content, motivation and engagement mechanisms, and features of the AR application. This serves to validate the design process relative to these criteria and identifies opportunities for enhancement, including opportunities for meaningful interaction. The resulting application demonstrates appropriate design strategies to support its target age group and focus. It provides a stimulating and flexible learning activity that can be readily integrated into the classroom and that supports the kindergarten transition to appropriate classroom behaviour by encouraging active engagement and collaboration, blending aspects of both outdoor and classroom-based activities.

Keywords: augmented reality; kindergarten transition; design; engagement; literacy primer

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1. Introduction

This paper presents a case study reviewing the design processes used to create the Forest Classroom (FC) experience: an augmented reality capable storybook for young children aimed at reducing disengagement and supporting teaching of curriculum topics to young students.

Teachers of primary school students have to support students transitioning from kindergarten to primary school. Schools implement 'bridging curriculum' programs to prepare the students for the more structured classroom-based learning environment, which is typically different from the play-based model in kindergartens O'Gorman and Ailwood [1]. The transition can be difficult when students are not being engaged by the learning and cannot sit quietly during lessons, disrupting their fellow students. Disengagement in the classroom is a growing concern in Australian schools, where 1 in 5 students [2] do not find school engaging, are less likely to learn and retain knowledge taught in class, and cause disruption to classroom teaching. Schools making use of mobile tablets in classrooms have opportunities to support engagement with content external to the device through the use of augmented reality (AR) immersive learning experiences. The design, development, and application of such immersive technologies in classroom can aid teachers in conducting their lessons. Related studies include AR experiences for teaching kids the alphabet [3], learning colour concepts [4], plant education [5], 2D & 3D visualisation of science topics [6] such as various bacteria types [7], language education [8], and for reducing anxiety in young children in hospitals [9].

The Forest Room concept [10] was developed to connect restless and disengaged students to nature as a calming medium. A space within the school, shown in Figure 1, is devoted to an environment where the 'outdoors is brought indoors'. Students who enter the room are encouraged to rest, recover, and refocus as they immerse themselves within nature through play-based learning activities using small wooden bamboo drums, basket weaving with ivy, various kinaesthetic activities, and mindfulness tasks.

Figure 1. Inside the Forest Room (**left**) and outside the Forest Room (**right**).

The success of the Forest Room has inspired the exploration of digital immersive technologies as a catalyst for classroom engagement. An AR application extends the concept into the Forest Classroom (FC) experience with the purpose of engaging young learners during the bridging process from kindergarten to primary school, educating them on caring for nature, and effectively employing augmented reality (AR) as an innovative tool in the classroom. The particular value of this work is in its consideration of issues relating to the overlap of the three areas of educational design, user experience, and AR application design. In this paper, we report on our case study on using AR to design, develop, and integrate AR experiences with teacher-developed activities into a single storybook. The key foci of this case study are:

1. Integrating educational content into the experience to provide value to the teachers.
2. Extending the physical Forest Room environment into an AR experience that provides motivation and engagement to students.
3. Designing and developing an AR application that adds meaningful value to the process and that is appropriate to the age group and context.

The research questions we answer are: What are the best practices for developing AR educational applications? How are these principles applied in practice?

1.1. Research Methodology

The research method employed is the descriptive case study [11], with reference to established frameworks as applied by Rovithis et al. [12], and a design science research strategy [13] as exemplified in the problem-centred approach employed in the work of Pappa and Papadopoulos [14]. This choice is based on the need to capture the complexities of the AR experience design process with respect to the specific perspectives employed to satisfy the multiple design goals. These perspectives are codified with respect to the frameworks described in Section 2 that capture the context and the relationships to external influencers.

The design method reported embodies principles used in the design of information systems within ambient environments [13]. Specifically, we report on integration of diverse design steps and stakeholders by explicitly reporting on the selected design themes: educational considerations relevant to teachers, the motivating mechanisms used to support students, and the application architecture relevant to AR experience developers. The system design is emphasised and represented in terms of formal frameworks in each of these categories. Just as in Pappa and Papadopoulos [14], evaluation of the solution design is achieved through critical analysis of comparable applications focused on each of the design themes. Other activities undertaken during the design process, such as requirements specification and progressive refinement in response to feedback, are explicitly mentioned only where they are of particular significance to this case study.

1.2. Application Features Overview

The FC experience consists of a mobile application and a storybook. The book provides an accompanying narrative as well as marker images to trigger AR content displayed by the application as shown in Figure 2. As the students and teachers follow the unfolding narrative in the book, particular pages can be scanned to further expand on the story and present the associated educational messages. These consist of animated 3D versions of the characters in the book who engage the students directly through their actions and spoken message. The application runs on mobile tablets, as these represent the safest solution for prolonged use by children around 5 years of age to access virtual environments. The software is developed using the Unity3D game development engine using facilities provided by Dreemar (https://www.dreemar.com/, accessed on 20 April 2023) to recognise images in the book and to overlay virtual content.

The curriculum topic discussed is one of sustainability and care for the forest, in keeping with the original Forest Room concept. Harry the Helmeted Honeyeater is a central figure who engages with the students. The students trigger the AR experience by tapping the circular 'multi-coloured jewel' icon representing Harry's jewel necklace. This activates the mobile device's camera as students trigger the AR experiences from individual pages within the book.

The welcome screen (Figure 3) provides direct access to a range of media resources: video content providing the learning plan, media clips describe the journey to save the forest and introduce a young forest keeper who shares her journey (Figure 4). The animated character Hettie invites the students to join in the adventure and a mini-game (Figure 5) to catch and categorise falling leaves, and the AR elements.

Figure 2. A selection of the activities within the FC experience: using the mobile camera to tap and launch the AR experience, Hettie drumming on mushrooms with holly sticks to accompanying music in the AR experience, and the AR experience with the 'Magical Talking Tree' being translated into the real environment.

Figure 3. Welcome screen of the Forest Classroom AR app.

Figure 4. Learning by audio and video clips included in the app.

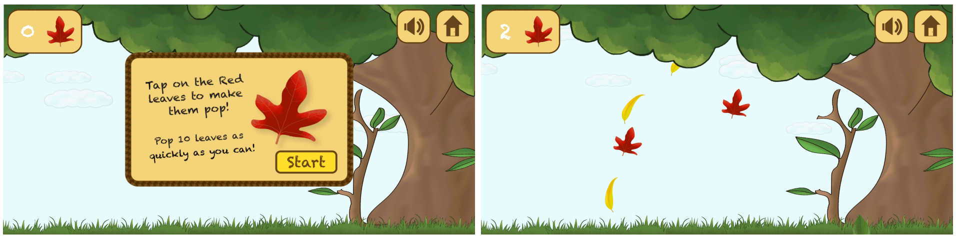

Figure 5. Interactive game to teach students colours and shapes by 'popping' the leaves.

1.3. Outline

The remainder of the paper is structured as follows: frameworks related to the three themes of educational AR application design, design for engagement and motivation, and AR experience architecture are described and reviewed in Section 2. The case study of the AR Forest Classroom experience is then presented in Section 3 with reference to each of the frameworks. The design choices are evaluated in Section 4 through comparison with related specialist applications, specifically, an educational augmented reality application covering comparable concepts, a literacy application targeted at the same age group, and an AR book design. The paper concludes by reporting insights resulting from this design case study in Sections 4 and 5.

2. Design Frameworks for an Augmented Reality Forest Classroom

Augmented reality can enhance teaching and learning, but further research is required to design experiences that use it effectively as a teaching tool [15]. In particular, issues identified include: ensuring a relationship between the AR design and the learning goals [15], assessing value in providing engagement to manage classroom behaviour [2], and designing an experience to support reliable and sustained usage [15], particularly for the target age group.

Three categories of design framework have been identified as relevant to the stakeholder requirements and to the design aspects of the case study reported in this paper. These relate to the design of AR applications for pedagogical purposes, to experience designs that target engagement and motivation outcomes, and to the design of AR application architectures focused on these areas. This section identifies and describes specific frameworks appropriate to each of these categories. These frameworks are then used to situate the FC experience case study that is described in detail in Section 3.

2.1. Augmented Reality Educational Experience Design

The FC experience engages students in learning about nature using attractive animated 3D characters and talking animals that come to life, sing, and play musical instruments. Students engage with the immersive digital experience that is overlaid on a real environment. AR in classroom teaching should contribute to capturing and holding the attention of students as well as support the educational experience by enabling learning and enhancing retention of the curriculum topic. Use of AR involves application of constructive learning directly to cognition and highlights the role of senses in perceiving and making meaning out of blended real and digital stimuli received by the brain [16]. How the brain cognitively reacts to augmented reality environments is an active research topic relating to the learning process to create a sense of presence, produce engagement, and hold attention [17]. Attention is a prerequisite to effective learning [18], and AR has the facilities and ability to capture one's attention [19].

Learning involves a change in behaviour through reinforced practice employing social and individual processes for the co-construction of knowledge [20]. Proponents of constructivist learning theories [21] focus on individual knowledge construction. Learning happens when the individual makes sense of the material. The theory of multiple intelligences [22] regards human intelligence as multi-dimensional, and the role of constructivist learning is to engage these multiple intelligences to create new cognitive structures. Teaching requires that learners build on their existing knowledge by actively applying prior knowledge and experience rather than passively absorbing what is presented to them [23]. AR experiences fit naturally into a constructivist approach where participants have the opportunity to manipulate and explore consequences during knowledge building [15].

AR applications have been developed for a wide range of purposes. Their use for educational purposes requires that the design be consistent with one or more learning theories. A review of a range of AR learning applications [15] identified some core principles specific to the learning experience. Pedagogy is the first consideration, with the AR design focusing on curriculum rather than technology. Educational AR applications need to work reliably so that the flow of learning is not disrupted by trying to accommodate software limitations. A significant constructivist benefit of an AR application is to support self-directed learning through interacting with the physical and virtual content. Such applications can then also be used outside the classroom, and the design can consider how well-informed third parties such as parents can support the learning. AR technologies have the potential to reduce barriers for physically and intellectually challenged students, but these factors do need to be considered during the design stage. Finally, the particular implementation platform should be consistent with the needs and skills of learners and teachers [24]. The FC experience design is assessed with respect to these considerations in Section 3.1.

2.2. Engagement and Motivational Design

Motivational design based on gratification theory [25] suggests that, while media engagement can be associated with relaxation, pleasure, fantasy, and escapism, there are additional factors around personal relationships, self-improvement, and social awareness that play a role. Media such as AR, where participants play an active role, adjusts attitudes [26] through linking needs and motives to media consumption behaviour. The theory of planned behaviour [27] predicts individual behaviour by considering personal beliefs related to desire (behavioural beliefs), opportunities (control beliefs), and social pressures (normative beliefs) but does exclude emotional and collective group behaviours. Engagement with technology artefacts is driven by technology acceptance models, such as the unified theory of acceptance and use of technology [28], which identifies factors such as enhancing personal performance, amount of effort, social recognition, barriers to use, hedonic motivation, costs and value, and habit as driving behavioural decisions. Individual personality traits, such as the big five classification [29] of extroversion, agreeableness, conscientiousness, neuroticism, and openness, are expected to interact with motivating factors.

Gratification theory [25] is extended in conjunction with flow theory [30] into a framework for engaging participants with AR applications by [31]. The framework elements relate engagement to the hedonic, emotional, and social benefits, which are factors present across several of the theories discussed. The FC experience design is evaluated using this framework in Section 3.2.

Hedonic benefits achieve motivation through providing a pleasurable experience. This is achieved by making the experience enjoyable using game-inspired mechanisms to increase fun and reduce boredom. Other hedonistic game player motivations [32] include opportunities to immerse oneself, explore, discover, and achieve. Physical activity is identified as a hedonic benefit linked to endorphin release, and AR experiences use this to distinguish themselves from sedentary applications. Flow represents the enjoyment of achieving complete focus in a particular activity and is achieved through balance of task complexity against development of skills, particularly where progression is clear and where effective direction and feedback are provided. Emotional benefits involve previous positive personal experiences (nostalgia) or visits to places [33]. Social benefits motivate through developing new relationships, enjoying existing ones, or increasing social standing within existing groups. Visible display of the social groupings encourage participation through the need to conform to social norms.

2.3. Augmented Reality Application Design

Design frameworks for virtual realities originally focused on the technical challenges of achieving a sense of immersion and presence [34] by manipulating technical elements, including image quality and tracking accuracy but also user experience factors such as the narrative and nature of interaction. AR applications in particular are decomposed into components for environment, objects, interaction, and lighting [35]. Integration of physical and virtual spaces [36] encourages designs that consider the spatial, sensory, and cultural nature of the setting as well as the relationships to, and between, participants. The application architecture of spatially aware applications typically distinguishes the client interface, with location tracking used by the participant, from the database used to coordinate all participants [37,38]. An alternative architecture framework [39] logically separates sensing, data management, scene alignment, and testing functions. Game elements in the client interface are designed at successive levels of abstraction [40], ranging from abstract game design processes through to concrete interface layouts. The design process itself can be framed in terms of AR-relevant heuristics [41,42] that ensure form and fit are appropriate to the user experience, while integrating physical and virtual content relating to the setting.

Common elements of multiple AR design frameworks are integrated into the framework by Acosta et al. [43], which focuses on the design of AR applications to support engagement through student motivation. This proposal is validated against the attention, relevance, confidence, and satisfaction (ARCS) model Keller [44] for motivational design with respect to learning. The components of an AR application particularly relevant to the Forest Classroom context described in Section 3.3 include: the user interface and interaction module, scaffolding and real-time feedback, access to/for teachers, and the technology choices made to integrate physical and virtual content. Aspects related to assessment and collection of learning analytics are outside the scope of the original FC experience but are being developed as part of a subsequent stage.

3. Description of Forest Classroom AR Design

This section presents the case study of the Forest Classroom AR experience, relating key design features to the frameworks described in Section 2. The goals of the study are addressed by planning effective integration of educational content in Section 3.1 using the AR learning framework [15] that was presented in Section 2.1, considering motivation and engagement in Section 3.2 using the AR adoption framework [31] that was described in Section 2.2, and following the process in Section 3.3 by using the framework [43] to design and develop an AR application that was covered in Section 2.3.

3.1. Augmented Reality Educational Experience Design

The school leadership, teachers, and the researchers developed the FC experience to teach the topic "saving the forest" to young kindergarten and primary-school children. The book used is an ordinary printed book whose illustrations can be used to trigger digital content in the application that is superimposed on the printed pages, enriching the reading experience [45] and providing engaging learning opportunities [46]. The rationale behind the embedding of the learning content is described with respect to the criteria of the AR learning framework [15].

3.1.1. Educational Principles

Students are introduced to the book's characters in the setting of a 'Magical Forest' and are encouraged to take the book in hand, read it, and interact with it using the AR technology to discover each aspect of the narrative. AR technology has been found to enhance students' engagement, motivation, and creativity in STEAM education [47]. The FC experience delivers educational outcomes using active learning [48] approaches that encourage students to engage with the forest animals, characters, and the forest environment. AR promotes interaction with the content of the book in fun and engaging way. This creates an emotional and psychological engagement with the characters in the book and helps to develop a deeper understanding of the book's subject matter. Active learning principles increase engagement and motivation among the students, as well as improve understanding of the course material [49]. Key themes are listening to the characters having conversations on topics of sustainability, investigating the consequences of having trees cut down, and experiencing how these affect the forest animals and environment as a whole. The scaffolding provided supports the child's developing literacy levels while hearing the conversations between the characters, which provides the student a sense of being in the scene as an observer to the conversation and being involved. Interactions with the real environment and virtual objects support learning through active play with virtual characters combined with the actions of turning book pages and manipulating the moveable parts [50].

3.1.2. Curriculum and Pedagogy Design

Adoption of AR technology in a school classroom requires that AR experiences be designed with curriculum and pedagogy in mind [51]. The theme chosen, related to nature and forest care, allows students to identify concerns around deforestation and explore how they can play a part in saving the forest as responsible individuals. This integrates with numerous resources already developed by teachers as part of the school's Kinder-to-Prep Bridging curriculum, to make the transition from outside kindergartens an enjoyable and engaging experience. The message that the book promotes of how the forest animal characters persevere together to protect their home environment addresses the curriculum topics and provides role models for restless students.

The FC book promotes and encourages early reading amongst the preschool students. AR technology is used to bring to life the two main characters in the book, Harry and Hettie. This enables students to engage with the story both passively and actively, as well as before, during, and after learning to read.

3.1.3. Stability in Interaction

The FC book can be used on its own as a conventional storybook but, typically, illustrations would trigger further content displayed on the mobile device. The 3D animations closely match the book illustrations and are presented overlaid on the images in the book to further reinforce the relationship. Moving the device emphasises their apparent physical presence. There are constraints imposed by the need to recognise the marker images, which requires sufficient and consistent light levels, and by the requirement that the pages of the book are not worn or damaged.

3.1.4. Self-Learning Capability

The FC experience can keep children motivated even without the immediate presence of the teacher. This property of AR has been linked to improved learning outcomes in other studies [52,53]. As an example, the talking magical tree (see Figure 2) is triggered by an AR marker but can then be detached from the book and placed in part of the classroom. The students can make the tree talk by a tap on the screen while the tree showers golden sparkles around the view of the student's environment. This provides a virtual instructor as part of a highly engaging experience.

3.1.5. Parent's Involvement

Parents have been encouraged to download the application and to read the FC AR book to their children, while encouraging initial feedback. The FC experience is self-contained, requiring no extra training on specific curriculum topics for parents. In addition, an AR experience stimulates enthusiasm, understanding, and reading skill outcomes [54] as parents and children interact.

3.1.6. Student's Background

The FC experience particularly targets students transiting from kindergarten to prep-school. The story content and format of the media used are adapted for use at this age level. Staging of activities from having the book read to the student, students interacting through AR, and allowing the student to read themselves are intended to support the student's journey at this age, while still providing an engaging and reusable experience. As in any multimedia device usage, usage times in young children also need to be limited to reduce potential risks of physical, social, health, and ethical problems [15].

3.1.7. Platform

The choice of platform for the FC application was dictated by the availability of iPads already used in various learning modules in classrooms. Tablets offer mobility, allowing students to directly engage with content, and have facilitated direct collaboration with others. Developing both the iOS and Android versions of the FC experience has allowed access to a wider audience. The printed book is usable, even in the absence of any supporting device. The combination of book and application provides opportunities for literacy development beyond that offered by each on its own.

3.2. Engagement and Motivational Design

The FC experience is part of the school's bridging curriculum for kindergarten students and recognises the need to address disengagement in a formal classroom setting. The extent to which engagement can be supported in the design is assessed relative to the AR adoption framework [31].

3.2.1. Hedonic Enjoyment

In a typical prep-level story-telling session, a teacher would read the book to the children, as most are still building their early reading skills. Students are intrigued by the story, especially the 'magical forest' theme. They then get to experience the book's characters come to life in 3D using AR, which allows further discovery supported by the narrative and enhances the reward associated with discovery while reading a book.

The experience engages across modalities through the audio, video, and 3D animations. Students can play 'Pop the Leaves' and receive reward in the form of scores and a sense of achievement. The design follows the approach that the "gamification" of a teaching and learning scenario can motivate learners by increasing interactivity [55], with best practices in game-play design by the consideration of parameters such as immersion, interactivity, congruence with reality, proximity, adaptivity, and complexity [56].

3.2.2. Physical Activity

Unlike conventional books, mobility is intrinsic in the AR experience, as students are released from their seats and able to move around the markers to get and share the best view. Detachable markers allow the experience to take advantage of the physical space in the classroom. The lesson can equally well be conducted in the school's garden or a nearby park to directly integrate the nature theme closer to the students.

3.2.3. Flow

Flow design balances challenge against achievement through the levels of difficulty provided in the leaf-popping mini-game. Flow is part of the emerging narrative, as the 13 pages of the book represent the developing adventures of Hettie and Harry as well as opportunities for further engagement. For example, the pages enhanced with an AR experience include a scene where the character is seen drumming on mushrooms with a pair of holly sticks. The music and sound effects provided in the AR overlay further develop this part of the plot and can be used as the basis for music lessons, such as learning a new song or nursery rhymes.

3.2.4. Emotional Benefits

The FC experience introduces characters and their concerns about the forest being cut down. This provides opportunities for students to develop empathy with these emotional and nostalgic feelings of loss. The friends in the book appear as small animals (bird, koala, parrot) who have bonded together for a common goal to save the forest (their home). The eagle expresses its emotion and is shown crying about the destruction of its forest home. The bird, Harry, who is helping to save their forest, encourages similar behaviour, providing opportunities to explore the emotional aspects of adjusting to the school environment.

3.2.5. Social Status

In a typical classroom learning session, the FC experience encourages young students to share, interact, discover, and learn together in small groups. Students move around the classroom to share their experiences with one another. Students who are more confident with mobile devices gain status by exploring more of the experience and sharing this with their peers. This supports the other students who benefit by observing and are then able to use the application independently.

3.2.6. Social Norms

Students tend to share their mobile screens with their friends, prompting everyone to discuss and comment on the AR experience and content, and supporting positive group work behaviours. Good listening behaviour is demonstrated when students need to listen quietly and attentively to the audio clips. Students also share their excitement with the class teacher after an engaging AR experience.

3.3. Augmented Reality Application Design

The design of the FC application began after the first draft of the book was written. The book authors had the vision of a narrative where young children would be able to relate to the magical forest theme, with the opportunity for the magic to be added through the AR application. The design team decided to introduce the two main characters of the story, Harry and Hettie, as an initial AR experience. This was followed by an activity where Hettie would play drums within the magical tree, and by the mini-game of 'Pop the Leaves'. The design of the AR facilities are further described in the context of the AR design framework [43], which focuses on the components of an engaging educational AR experience.

3.3.1. User Interface and Interaction Layer

The user interface needs to engage young students and launches into the welcome screen (Figure 3) where students can immediately use the on-screen buttons to select media clips introducing their learning journey (Figure 4), play the mobile game called 'Pop the Leaves' (Figure 5), or initiate the AR experience. The student points the camera to one of the AR capable pages in the book to trigger the associated AR content (Figure 2).

3.3.2. Scaffolding and Success Opportunities

The AR book presents a linear narrative introducing the magic forest and developing the two main characters. The AR elements provide as success opportunities the reward of additional content and an opportunity to develop particular topics in more detail. For example, the drumming activity (Figure 2) supports teachers having real drums in the classroom to practice gross motor skills for cognitive brain development exercises. Along the adventure, fun starts where drumming and singing are included into the AR experience and where the unfolding story shows a new world where characters and animals come to life.

3.3.3. Input, Sensing, and Registration

Both detachable and non-detachable AR markers are used in the AR experience. Non-detachable markers anchor the content to the book, while detachable markers such as that used for the magical talking tree allow students to resize, move, and rotate the tree and to show it in various places in the classroom.

3.3.4. Real-Time Feedback

The FC application is responsive in that animated content is provided when the marker images are recognised. Currently, the animated content is pre-scripted and does not support direct interaction with the students (the placement of the magical tree being an exception).

3.3.5. Engagement with the Teacher

The interface design and engagement are intended to support activity initiation by the teacher. This can be an interlude with one of the AR topics during reading the book to the class or an individual opportunity for a restless student to play the game. The visibility of the tablet screens ensures that the classroom teacher is able to monitor progress. Further developments will use analytics data shared via a dashboard with the teacher.

4. Expert Heuristic Evaluation of Design

The FC experience uses AR to support educational and motivational goals, using the storybook metaphor to ensure that teachers and young children relate to its purpose as a literacy development tool. It is distinctive in its focus on an age group where learning is best supported by exploration and engagement. Teaching abstract principles of sustainability is achieved through the imaginative narrative and the engaging characters that are brought to life in 3D through AR so that students identify with the characters and their plight. Motivational and engagement outcomes are explicit in the design process. This form of bridging activity is well suited to those who are easily distracted by classroom learning by providing opportunities to get physically active and engaged.

Currently, only five pages in the book are AR-enabled, pending development of further content. This is an opportunity to introduce other learning topics (such as the drumming described previously) now that a design template has been established. Anecdotal feedback suggests that the students engage enthusiastically and want more content once they have completed all the activities. FC encourages conversations between teachers and students on the topics being presented. Reuse is supported by opportunities to selectively engage with portions of the content: as a storybook, to teach awareness of nature, an active collaborative classroom activity, a distraction game, or as a reading primer. The FC experience makes use of equipment readily available in many classrooms (books, tablet) and can be deployed without significant prior preparation.

Due to COVID-19 restrictions, it was not possible to formally trial the FC experience with children aged 5 to 7 years during their lessons. Engaging experts in a heuristic evaluation [57] of the case study design (Section 3) and application relative to the frameworks described in Section 2 was instead used to validate the outcomes of the FC experience design. The lack of access to students meant that we were not able to perform evaluations that required student evaluation of the application, as conducted by [58].

Six experts with experience and expertise in at least two of the fields of (a) user interface design, (b) AR application development, and (c) education were invited to evaluate the FC AR application and the accompanying AR-capable book. The experts were provided with:

1. The Forest Adventure AR application via the Apple App Store and Google Play Store together with instructions to download and install the app on their personal device.
2. The Forest Adventure AR Book as a 30-page children's storybook about the adventures of Hettie and Harry in the forest.
3. A task list to complete, including downloading the application, installing it, reading the AR-capable storybook, triggering the AR experiences on the storybook pages, playing the "Popping the Leaves" game within the AR app, and finally giving their feedback.
4. The feedback form (see Table 1).

Table 1. Feedback form with heuristics and quantitative results.

EC	ME	AR	Feedback Form: Evaluation Criteria (1—Very Poor), (2—Poor), (3—Moderate), (4—Good), (5—Excellent)	Std Deviation	Mean
✔			1. Learning Content Design & Assessment: AR experiences facilitate the organisation of the content pieces and learning objects to achieve the primary goals and feedback to the learning programs.	1.10	3.17
✔			2. Motivation to Learn: AR experiences use e-stories, games, simulations, role playing, activities, and case studies to gain the attention and maintain the motivation of students.	0.98	3.83
✔			3. Support Students' Curiosity: AR experiences should enable cognitive curiosity through surprises, paradoxes, humour, and dealing with topics that already interest the students.	0.76	3.83
✔			4. Educational Quality: AR experiences inserted in the scenes together with the possible actions and interactions contribute to the teaching–learning process.	1.38	3.50
✔			5. Evoke Students' Mental Imagery: AR experiences appeal to the imagination and encourage recognition to create a child's unique interpretations of the characters or contexts.	1.22	3.50
	✔		6. Fit with User Environment and Task: AR experiences use visualisation and metaphors that have meaning within the physical and task environment in which they are presented. Visualisations and metaphors match the mental models that the user has based on their physical environment and task.	1.03	3.67
	✔		7. Form Communicates Function: The form of a virtual element relies on existing metaphors that the user knows in order to communicate affordances and capabilities.	1.14	3.00

Table 1. *Cont.*

EC	ME	AR	Feedback Form: Evaluation Criteria (1—Very Poor), (2—Poor), (3—Moderate), (4—Good), (5—Excellent)	Std Deviation	Mean
	✔		8. Minimise Distraction and Overload: AR experience designs should work to minimise accidental distraction due to cluttered, busy, and/or movement-filled designs.	0.63	4.00
	✔		9. Fit with User’s Physical Abilities: Interaction with AR experiences does not require actions that are physically challenging, dangerous, or that require excess amounts of coordination. All physical motion required should be easy.	0.52	4.67
		✔	10. Adaptation to User Position and Motion: The system adapts such that virtual elements are useful and usable from a variety of viewing angles, distances, and movements that will be made by the user.	0.75	3.83
		✔	11. Alignment of Physical and Virtual Worlds: Placement of virtual elements should make sense in the physical environment. If virtual elements are aligned with physical objects, this alignment should be continuous over time and viewing perspectives.	1.03	4.33
		✔	12. Accessibility of Off-screen Objects: Interfaces that require direct manipulation (for example, AR and touch screens) should make it easy for users to find or recall the items they need to manipulate when those items are outside the field of view.	1.26	4.00
		✔	13. Accounting for Hardware Capabilities: AR experiences should be designed to accommodate the capabilities and limitations of the hardware platform.	0.41	4.83

After completing the tasks, the experts provided their feedback using score ratings and comments for each of the 13 criteria for the heuristic evaluation using the feedback form. The form focuses on how each heuristic is satisfied by rating from 1 (Very Poor) to 5 (Excellent). For each rating given, the experts commented on the criteria used to base their ratings, to explain the severity of any problems, and also to suggest solutions for resolving issues highlighted.

The heuristic evaluation is based on the three categories identified in Section 2, comprising: (i) the support for educational content (EC), (ii) motivation and engagement mechanisms (ME), and (iii) features of the AR application (AR). Heuristics H1 to H5 for educational content are adapted from the verified heuristics for children’s mobile-based learning applications [59], which consider the developmental abilities of young children in learning using mobile applications, such as their attention span, cognitive abilities, and physical dexterity with respect to the different ways young children interact with technology, such as using touch screens. Heuristics H6 to H9 provide criteria for the motivational and engagement aspects, and H10 to H13 reference the interactions relative to physical and virtual environments, as well as hardware issues related to mobility and positioning during the AR experience. Usability heuristics [41] and the evaluation criteria for learning objects in AR for smartphones [60] provide criteria for evaluating the usability of AR-based learning objects and highlight the importance of considering usability when designing AR-based educational experiences. The heuristics include criteria for considering the user’s spatial and temporal context, providing clear feedback to the user, leveraging the affordances of the AR medium, and providing effective guidance to support the user’s interactions.

4.1. Results

Each of the experts provided useful assessment of the usability and overall user experience, and provided valuable feedback and comments on the effectiveness of AR for engagement and learning outcomes.

4.1.1. Educational Content

The top-rated heuristic in the education content category (H2, M = 3.83) indicates clear instances of motivation for learners to be able to apply the knowledge and skills acquired through the story in the book, where experts noted that the "learning experience was very controlled and discrete" and was "appropriate and suitable given the story being told". Two of the experts agreed that there was an "accurate depiction of story being told—educational opportunities and messaging to help in their understanding/appreciation of environmental/sustainability factors", with the physical book providing the attention and motivation in using AR experience to support the main learning content. Accurately depicting the story in the AR application ensures that learners can maintain the flow of the story and ensures that the application maintains engagement and motivation.

Immediate and meaningful feedback is provided by the "animated characters asking questions posed to the reader as provocations", without which there would be "limited opportunity for further imagination". Experts agreed (heuristic rating H3, M = 3.83) that "going beyond the written text and having the characters do more than what is written in the printed text have perhaps achieved this particular aim which supports a student's curiosity" to stimulate learning. The AR experience provides a learning experience that allows students to engage in active investigation that would not be possible with just the book format.

For effective learning to happen (H1, M = 3.17), one expert suggested "allowing the reader some flexibility to be creative and to interpret the text in a way that is meaningful to them", as "this is often the appeal of reading, providing the element that instills a life-long love for reading". Experts concluded that the "focus is on English/literacy development for school-aged children, children are expected to make connections to their personal lives and to others (classmates) and to recognise/recall key ideas/literal information in the text" facilitates collaboration and social interactions among learners while noting that "role-play rather than activities and games, would be a good alternate decision". The application contributed to the teaching–learning process where "at times the characters even helped with vocabulary building"; however, an opportunity was identified for "getting the characters to explain the implied meaning and to ask questions as provocations that a teacher/adult can build upon" to increase the quality of learning for the children. Here, an AR application intended to provide a bridging experience also supports skills in several other curriculum topics, such as enabling children to develop important literacy skills, such as reading comprehension and vocabulary development.

A key point noted with respect to mental imagery (H5, M = 3.50) is that "the story itself provides learning and awareness opportunities", and the use of AR for extending students' interpretation is "supplementary to the actual story and messages". To enable better "natural reading and use of AR affordance" by young children, one expert suggested including "additional elements in places to aid comprehension/alignment with the printed text" and "needed more interaction, even minor, on each AR element to evoke further mental imagery." Where the "reader is to use their own imagination and create their own unique interpretations", improvements to the authenticity of the AR experience are needed to provide "realistic experiences that align with the real-world context in which the learner will apply the knowledge". The multi-modal opportunities afforded by AR require care in ensuring that the elements presented trigger learners' imaginations to ensure they engage by being immersed in the experience. In the FC application's characters express their emotions to reinforce the message in the story.

There was relevance in the AR experiences to the learning objectives of the education content (H4, M = 3.50) that aligned with the story in the book. Experts noted that "the AR book is a great concept to provide engaging story telling accompanying a book format", "visual elements work well with the story", and added that "all visual elements either fit with what a child would know/understand as the text is read aloud to them, or will help to expand their vocabulary". Most agreed that the "placement of the visual elements were well considered", but one expert felt that the "virtual elements are small" and that enlarging the size would provide better experience for small children. The FC experience demonstrates how AR applications enhance the narrative in books to help children develop important literacy skills while also fostering creativity and imagination.

Engaging and captivating FC experiences encourage exploration and discovery beyond the interactive experience, leading to a more in-depth understanding and appreciation of the storybook's themes and characters.

4.1.2. Motivation and Engagement

The most supported heuristic in this category (H9, M = 4.67) indicates that the overall accessibility of the FC experience has the potential to significantly improve the experience of the storybook; physically moving around the AR book while targeting and triggering the AR experiences from the book pages was easy and able to support learning. Better engagement with digital assets was the common suggestion, with one expert commenting "nothing for me to manipulate ... tried tapping on things but nothing happened". Suggestions were made to add more actions using "more movement and engagement with characters ... as now only slight body movements such as walking". Another expert felt that " AR experiences should be accessible and inclusive, accommodating the needs of all learners including those with disability" and noting that children with auditory processing issues or delays will find it "challenging to process all that is said without the support of animations or other illustrations/visual supports that can remain on the screen and support processing". The consensus is that the experience needs more opportunities for interaction and visible affordances that indicate where interaction is possible. AR does ensure text is supplemented with graphics, animations, and sounds, but the experts provided a reminder to ensure that content is accessible under various cognitive conditions and attention spans.

The AR experience was identified (H7, M = 3.00) as representative of good motivational storytelling with "excellent interactions and amazing story portrayed in the book", "AR experience was enjoyable and even delightful", and "It was an engaging experience". Suggestions to make it more engaging included "more touch screen interaction could be supported". We would favour strategies that allow the learners to engage directly with the characters in space, but technical limitations may require interactions be managed through the touch screen.

The second highest rating for the category (H8, M = 4.00) indicates that experts agree that the AR elements add value to the learning experience rather than being distracting and complement the educational content rather that overwhelming it. However, there was a level of visual distraction with the need to "keep turning the pages of the book for viewing the different AR, however, it is unclear on specific learning objectives" this would enhance. To prevent additional overload to the visual imagery, experts suggested "reconsider(ing) choice of sound to make audio more engaging", using creative scenarios such as "AR of Hettie in a field of violets and laughing". To address better child motivation and increase the overall engagement, they suggested "get(ting) the characters to ask questions as provocations to help the child to make connections with their own lives". Some experts felt that the recorded audio and music were an "element of distraction" to engaging learners, as "the water sound of page 6 was rather loud, possibly abrasive" and "sound is too loud". Another expert felt that the "instructions are excellent and clear to use AR & App in the book. Sound and music is often excluded in some pages and would be useful and impactful for learners to immerse in the AR experiences". The visual elements of the AR experience add value, but opportunities to exploit the benefits of the audio still remain. In particular, being able to participate in a conversation with the characters would be an opportunity to increase engagement with the application. One expert highlighted that, with the additional cognitive load associated with the use of AR, kids enjoy the FC experiences in a fun and motivating way, helping to reduce the anxiety in some kids and creating a more positive learning environment.

Issues were identified (H6, M = 3.67) with loss of the AR tracking where the digital characters would disappear “when reading this book casually, such as sitting up in bed, maintaining a good viewing/scanning angle was more difficult" and that “3D contents were engaging, however, the overall imagery could be confusing since 3D contents don’t interact with the page”. The paper book may have been the factor, so needs to consider book ergonomics, "a strong yet flat book structure to enable best position for user to explore”. Addressing this challenge with the technology will enhance the engagement, as “it refreshes the book format and creates engaging experience”, and “pages with AR dialogues are great”. These are challenges with using the experience in typical home and classroom settings that will need to be addressed by improvements in the AR toolkits used to create applications.

Use of the FC experience as an interactive story creates engaging and immersive experiences for users by utilising multi-sensory aspects, including for those with learning or reading challenges. This includes visual and auditory elements to reinforce the story and improve the user’s understanding and engagement.

4.1.3. Features of AR

The two highest-rated heuristics on the features and effectiveness of the AR app relate to the hardware capabilities (H13, M = 4.83) and the alignment of physical and virtual worlds (H11, M = 4.33). The ability and ease of overlaying the AR experience on the book using a mobile device included the comment, “when AR content popped up, the drawing on the page became irrelevant and introduced visual confusion”, suggesting that an AR experience should provide feedback in multiple modalities of the mobile device, such as visual, auditory and possibly even haptic to enhance the learner’s engagement and understanding. Hence, one expert “recommend(s) to either: render a ground and cover entirely the 2D drawing or create 3D contents that interact with the 2D page” and “the layers in some of the scenes caused the AR to be submerged, maybe an overlay on the ground would help”. AR applications can choose to either integrate multiple elements (e.g., book and device) or substitute one with the other but should avoid allowing them to coexist independently where they can interfere with each other.

Accessing off-screen objects was rated (H12, M = 4.00) as “simple and easy to operate”, “highly accurate page scanning - quick and mostly effortless”, and so experts suggested improving “touch screen interactions” which they felt were “not fully utilised”.

While experts noted that the “assets closely matched 2D depictions in book”, it is still challenging for a young child to adapt to the position and motion while using the AR app (H10, M = 3.83), especially without adult assistance or supervision, with it being “a good fit for a 6 year-old, who could scan and review the AR elements, however found it difficult when elements popped and then disappeared”. This challenge was due to the limitation of an AR experience for an AR-capable book which “could not scan and maintain AR elements at a distance greater than 30 cm”. Keeping the mobile device steady was also identified as challenging, where one expert noted that “tracking is pretty good. It seems the app works best with the pages that are flat on a high surface, like a table”. While this is a limitation with the underlying technology that continues to improve, the application design needs to be aware of these “seams” [37] in the experience and ensure that the experience is robust when these issues occur. When tracking is recovered, the experience repeats any content that may have been missed. Markerless tracking also provides a way to disconnect content from requiring a marker to be tracked continuously.

Expert feedback and testing heuristics played a critical role in the evaluation of the FC experience, in creating a more effective and user-friendly design. AR has many unique features that set it apart from traditional classroom settings, such as the ability for students to move around and interact with the environment in real time. However, relying solely on expert heuristics evaluation may not fully capture the variability and complexity of the user experience in the real-world context, although they can anticipate some of the perspectives as the target audience.

5. Conclusions

This case study described the design of the Forest Classroom augmented reality experience. The analysis in Section 2 reviewed literature in educational, user experience, and AR application development to identify a framework of best practices for developing educational AR experiences. We applied these principles in the design and development of the Forest Classroom application and explained how each element of the framework was mapped to a feature of this application. The design process was assessed with respect to the three goals of: enhancing engagement for kindergarten transitions, integrating curriculum topics, and building an effective educational augmented reality experience. The analysis approach employed frameworks related to each of the three goals, and a comparison with related specialist applications was carried out. This allowed the complexity of multiple overlapping features of an experience to be isolated to identify their role relative to the complete experience design.

The FC experience does involve collaboration when using AR, although this emerges through the physical interactions of the participants. The use of images and content from the book as the basis for AR markers and AR content is common to both experiences. Future FC versions could be enhanced through cooperative design or by using reward cards to motivate children to complete activities.

Although the FC app has limited interaction opportunities, it does include game elements and opportunities to learn implicitly across a wider variety of concepts (such as appropriate classroom behaviour through interaction with others while exploring the story).

The FC experience focuses on learning outcomes related to literacy and uses 3D animated characters as reward and feedback for engaging with reading, adapting existing teaching materials that are intended to introduce and complement a diverse range of teaching activities. FC integrates an educational goal with motivation and engagement elements, combined with narrative, AR content, and a mini-game. FC employs an interface economy to minimise distractions using multi-modal communication. Visual and interactive elements provide clear feedback.

The FC experience represents a niche educational AR application that is notable in a number of ways. While overtly a reading primer, it also includes elements to support the transition from kindergarten to prep-school by providing motivational mechanics to engage students. The physical activity and collaboration opportunities afforded by the AR elements align with appropriate classroom behaviours while still supporting students who might be disengaged in this environment. The storybook integration and nature of the content and concepts covered are particularly appropriate to the targeted age group. The experience can be used to introduce a range of curriculum topics.

Further development of this prototype focuses on improving opportunities for interaction with the AR content, supporting analytics to track the learning that takes place, and providing authoring opportunities to expand on the range of topics supported.

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