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Multidisciplinary Development Process of a Story-based Mobile Augmented Reality Game for Learning Math

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***Abstract*—Despite the high number of educational games released, only a few games have a strong story that is more than an excuse for players' actions. Furthermore, even fewer story-based games utilise the affordances of augmented reality (AR) to concretise abstract concepts while engaging players. Based on our literature review, we were inspired to merge AR into a story-based educational mobile game for teaching fractions to elementary school students. The game Tales & Fractions was created through a two-phase multidisciplinary development process. In order to successfully integrate AR into a story-based educational game, we employed an adapted version of the Scrum agile software development method implemented by a multidisciplinary team of experts from computer science, pedagogy, design and arts. During the development process, we faced many issues that other story-based AR game developers could meet. We summarised the encountered issues with our solutions which could be useful for developers to avoid common pitfalls and to enrich the user engagement.**

***Index Terms*—Multidisciplinary, Storytelling, Educational game, Augmented Reality, Game-based learning, Mathematics**

I. Introduction

Educational games have often been touted as being engaging, with this often being a key reason for making a game about a specific learning topic. But what aspects of a game make it engaging? There are numerous answers to this question ranging from the preferences of different player types [1] to a myriad of motivators that games can possess [2]. We elected to look into a rarer combination of two such potential engagement factors: Augmented Reality (AR) and stories. AR has been shown to be a potentially useful tool in education when used well [3], [4], and it has been associated with a multitude affordances in education [3], [5]–[7]. Moreover, the use of stories is another potentially effective way to engage players in a game [8]–[10]. AR has garnered more traction in educational games over the last decade as various development toolkits have made its implementation easier [11]. However, the use of AR in representing concrete mathematical manipulatives, which help bridging the concrete real world to the abstract mathematical world [12], has so far been minimal in educational games. Moreover, the use of stories seems, according to our literature review, somewhat passive in research-based educational games. A majority of such education games do not have a story and when they do, it often seems more of an afterthought rather than a deliberate attempt of enriching the learning experience.

It is clear that making a good educational game with an appealing story and AR-based concrete manipulatives would be challenging. We aimed to overcome this by establishing a multidisciplinary group of experts from three disciplines – computer science, arts & design, and pedagogy – to create an educational game Tales & Fractions that uses a story and AR to teach elementary school students about fractions. We start this study by investigating concrete manipulatives, and how stories and AR have been used in educational games in the past. Once the background is established, we describe the multidisciplinary conceptualisation and development processes of Tails & Fractions, including issues faced and our solutions. The results of this study can be used as lessons learned for educators, researchers and developers interested in harnessing the power of storytelling and AR in educational games.

II. Related Work

A. Concrete Manipulatives

Concrete manipulatives, such as fraction rods, can be beneficial to the student's learning of abstract mathematical concepts. Already in the 1960s Dienes proposed that multiple representations of concepts (i.e. the multiple embodiment principle) help bridging the concrete real world to the abstract mathematical world [12]. Concrete manipulatives are example manifestations of the multiple embodiment principle. Later, research has produced evidence suggesting that learning with concrete manipulatives outperforms traditional learning that focuses on abstract math [13]. In particular, concrete manipulatives can be helpful in the first stage of the Concrete-Representational-

Abstract learning sequence where the learner first becomes familiar with the abstract mathematical concept [14].

B. Use of Stories in Education Games

Despite the many angles from which researchers have assessed serious games, the aspect of stories in education games has somewhat been overlooked. We analysed a total of eight literature reviews [4], [11], [15]–[20] that covered 189 previous studies on serious games. Out of these we analysed 176 papers to find information on story-based education games. Our attempt was to get a wide spectrum of serious games, thus we focused on specific groups of games: 21st Century Skills, Education Games, Physical Rehabilitation, Health Care, AR Education Games, and Game-based Learning. Within some groups we found only a few games using stories; for example, in the Physical Rehabilitation and Health Care groups we identified only one game with a story from a total of 49 games.

Our definition of a story is quite simple. A "strong story" has a beginning, a middle point and an end. Despite this quite simple definition a number of games were ranked as to having a "weak story" essentially due to giving a simple excuse for the player's task at the beginning of the game, but no additional references to the story were made afterwards. Additionally, in some papers there was a fleeting mention of a story, but no further remarks to it were made later [21], [22]; due the lack of clarity these games were not listed as having a story.

Out of the analysed 182 studies only 20 games utilised "strong stories" as per our definition. Furthermore, it should be noted that for nearly all the games we relied on the descriptions of the authors. Only a handful of games were available for testing, or had footage available to see actual gameplay. Additionally, with the exception of Crystal Island [23], [24], there was very little focus on the reasoning as to why a game would have a story. In most cases a story was mainly mentioned in passing before moving on to other topics.

C. AR Education Games

We also investigated previous research on the use of AR in education games, and how they were coupled with storytelling. Three of the eight review papers focused on AR games. The total number of covered games was 56 of which we analysed 49. Out of these games, 10 and 6 were categorised as having a "strong story" and a "weak story", respectively.

Koutromonos et al. [19] conducted a review on the use of AR in education covering studies from 2000 to early 2014. A half of the eight reviewed games had some sort of story. This relatively high number is partly due to two games being from the same author [25], [26] and the games being very similar in their design. The remaining two games had what we labeled as "weak story". Interestingly, Echeverria et al. [27] focused briefly on discussing the importance of having a narrative as a component to make an immersive experience. However, the story in the game is presented only as a simple excuse for the players to collect space crystals.

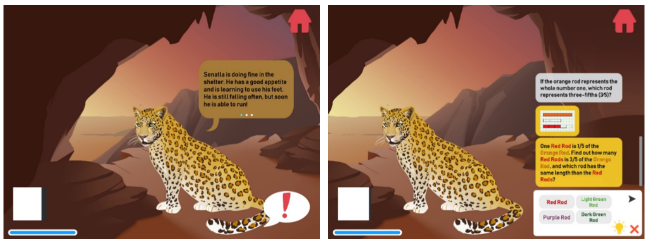
Fotaris et al. [4] conducted a systematic review on AR games between 2012 to 2017 focusing on five aspects AR games: instructional and learning approaches, environment & device used, topic, research methods, and results. Only two of the 17 discovered games utilised stories. In the case of Hendrys et al. [28] game, the focus on reading comprehension inherently involves stories. In the case of Leometry game [29], the players were quizzed on the effectiveness of the story, which yielded mainly positive results, with notions that the immersiveness could have been increased.

The literature review by Laine [11] analysed 31 mobile educational AR games published in 2012-2017 from the perspectives of general overview, pedagogy, AR features and used AR platforms, and gaming, and presented 13 guidelines to facilitate the development of educational AR games. Most of the analysed games were found to be treasure hunts and/or puzzle games, and whilst some games had adventure and role-playing characteristics that typically involve a story, the study did not investigate the use of storytelling in depth.

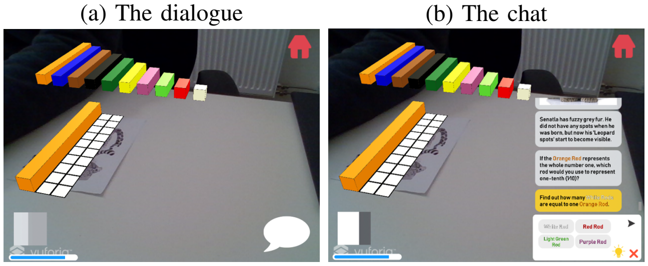
III. Game Conceptualisation and Motivation

A multitude affordances of AR in education [3], [5]–[7] and storytelling [8]–[10], diverse ways of using AR for learning a variety of subjects [11], [19], [30], and the pedagogical and motivational potential of the combination of mathematical manipulatives and storytelling, as witnessed by a previous study [31], inspired us to develop a novel game concept that combines a strong story and virtual AR manipulatives to engage players in learning fractions through rich content and interaction. The game conceptualisation begun with the principle that manipulatives can help concretising abstract mathematical concepts. Based on this, two key decisions were made on the pedagogical approach: (i) the pedagogical content of the game was to focus on the basics of fractions, and (ii) the game was to allow the player to experiment with fractions through AR-based fraction rods where each colour represents a certain length, thus allowing one to perform calculations on and form relationships between whole numbers and fractions.

Educational games have been recognised to possess a myriad of motivators that can help keeping learners engaged in the learning process [2]. *Fantasy*, manifested through storytelling, fraction *challenges* coupled with concrete fraction rods, and *relations* to co-players as well as to the game characters were among the key motivators that were baked into the foundations of Tales & Fractions. The story of Tales & Fractions follows two leopards, mother and her cub Senatla, who interact with the player through a dialogue and present fraction challenges to the player. The game's UI was designed to enable rich and efficient touch-based interaction, where the player could easily change between the main modes: the dialogue, the chat, and the AR rods playground. These modes of the UI are illustrated in Figure 1. The leopards' dialogues with the player are presented in the slide-in chat window as a history log. The chat also records the player's answers to fraction challenges, and presents hints and feedback. The player can open the AR mode to find a solution to the challenge with virtual fraction rods that are populated on an "AR playground" in various ways depending on the challenge at hand. The chat window is also available in the AR mode, so that the player can easily check the challenge description and hints. The goal of dividing the UI into the three modes was to avoid cramming the screen whilst providing the player with rich interaction methods.



(a) The dialogue (b) The chat



(c) The AR mode without chat (d) The AR mode with chat

Fig. 1: The modes of Tales & Fractions: The chat is available as a slide-in in the dialogue and AR mode.

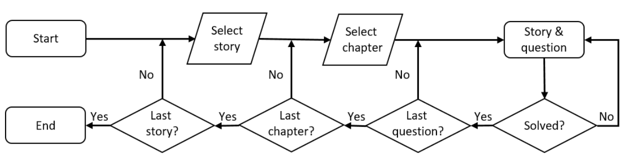


Fig. 2: Gameplay flowchart

Figure 2 shows the gameplay flowchart, where a single game consists of one or more stories that can have one or more chapters. The chapters in a story build on each other and advance the narrative by presenting content using text, images, videos and fraction challenges. For example, when the first chapter teaches about the basics of fractions, the next chapter talks about proportionality. The story is finished when all its chapters have been solved. The creation of the story and the fraction challenges was led by pedagogical experts.

In addition to the motivators mentioned above, we also aimed to support the *technology* motivator by choosing approaches that many today's children are familiar with: gamification, mobile technology and AR. A combination of these has been seen in several popular games, such as Pokemon GO and Harry Potter: Wizards Unite, in the recent years. Tales & Fractions was implemented for Android tablets using the Unity3D game engine and the Vuforia AR library. The details of the development process are described next.

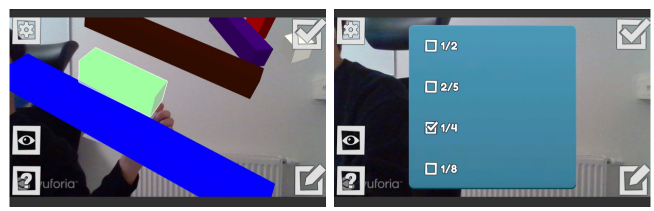
IV. Development Process

The game concept was materialised through two phases of development during which two versions – a proof-of-concept and a fully featured game – were created.

A. First Phase: Exploration

A first proof-of-concept version of Tales & Fractions was made by three programmers at an Object-Oriented Analysis and Design course at the Luleå University of Technology during eight weeks in 2017-2018. The workflow was based on the Scrum agile software development method [32]. The students did not have artistic, design and pedagogical expertise. Due to the absence of expertise in these key areas of game development, the development cycle had only two steps: (i) weekly sprint meetings to check the progress and test different versions of the proof-of-concept, and (ii) game programming to build the system with core functions. The development was supervised by a computer science and gamification expert.

The proof-of-concept was developed for the purpose of testing out the game idea and functions that emerged in the conceptualisation process (Section III). The game's UI and content were not in focus at this phase; however, the key functions were prototyped and tested, such as rudimentary AR rods, two challenge types (short-answer and multiple choice), and image/video presentation (Figure 3).



(a) The AR rods (b) The multiple choice

Fig. 3: The core functions of the proof-of-concept

The AR rods were implemented using a printed marker image that had no relation to the story. Additionally, the game had an invisible surface on the marker on which the AR rods were placed (Fig. 3a). The Unity3D physics were applied to the AR rods (e.g. rod collisions, gravity) for more realistic reaction between the rods and the player. Two types of challenges were developed to present fraction problems to the player: multiple choice (Fig. 3b) and short-answer. The proof-of-concept was also able to present images or video clips which were intended to enrich the story.

During the development and testing of the proof-of-concept, several issues were discovered that guided the next development phase. These issues are summarised in Table I, and our solutions to them are explained in the next section.

B. Second Phase: Multidisciplinary Development

The development team was expanded with experts from arts & design and education. Due to the larger size of the team it was divided into three groups, each representing a specialisation: programming, art direction & design, and pedagogy. Communication between the groups was done by a single team leader. Figure 4 shows the multidisciplinary work and collaboration among the groups.

A somewhat adjusted Scrum methodology was followed, with monthly meetings and weekly "confirmation" discussions, as presented in Figure 5. During a "confirmation", the

TABLE I: Summary of issues with the proof-of-concept

Issue	Area	Description
Poor UI & interaction design	UI	The application was designed without considering user experience.
Hidden information	UI	The game progress information was hidden in a place where was not easy to check at any time.
Lack of consistency	UI	Lack of consistency in the design aspect has negative impact on user experience (e.g. Random marker image).
Difficulty of AR rods control	AR	Because of Unity3D physics, the AR rods were difficult to be placed in the right orientation.
Invisible surface	AR	The lack of boundaries causes the AR rods to fall off the surface by accident.
Fixed number of AR rods	AR	It was not possible for the player to add more AR rods when needed.
Target devices	Opt[a]	The proof-of-concept version was developed for PCs rather than tablets.
Overused resources	Opt[a]	The game overused the device resources for rendering (e.g. textures, light).
Camera overuse	Opt[a]	The camera was always in use to detect the marker and visualise AR contents regardless of the challenge type.

[a]Optimisation

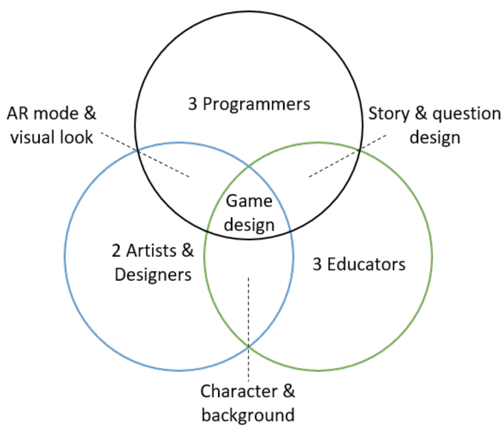


Fig. 4: Multidisciplinary work

pedagogy and design experts voiced their opinions on the current state of the game and what still was required or would need to be improved. This process was repeated monthly until all parties were sufficiently satisfied with the game.

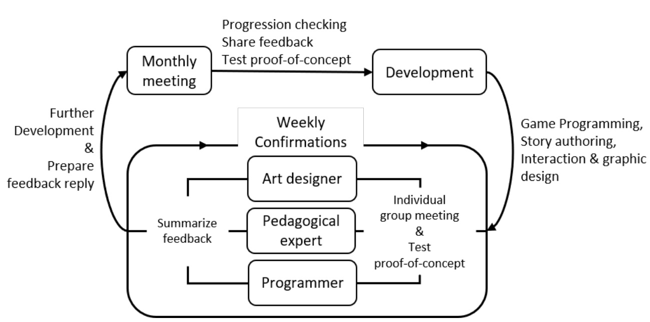


Fig. 5: Development cycle of the second phase

Many aspects were adapted during the second phase. For example, the UI was redesigned due to the inclusion of story, characters, new types of challenge, and interaction design. The AR mode had several updates to provide better user experience. Moreover, a number of changes were made to the project and asset configuration for optimising the game in order to have a good performance on Android tablets. Tables II–IV summarise the identified issues and our solutions to them in storytelling and learning content, UI and optimisation, and AR, respectively.

TABLE II: Issues & solutions regarding storytelling and learning content

Issue	Solution
Make the content system extensible	We designed the architecture to support multiple stories, each having a number of chapters comprising story snippets and challenges.
Match the learning content to target users	We based the learning contents on the Swedish curriculum.
Fusion of the story and the learning content	We divided the chosen learning topics into chapters based on the curriculum, and embedded learning content in the story progression.
Unappealing story	We utilised characters, facts about leopards, dialogue, drama elements, and interactive challenges to make the story intriguing.
Time consuming tutorial for introducing the rods	The original tutorial had a staircase frame that the player was asked to fill with rods. This took a lot of time, so we changed the tutorial to make a simpler pyramid instead (Fig. 6a).
Too strict player input check	For short-answer challenges, the game interpreted even correct answers as wrong due to the missing data in the correct answers pool. So we added all likely answers to the pool (e.g. 600, 600g and 600 grams etc)
Different representations of fraction notations	Players use only multiple choice challenges to submit fractions. Elementary school students in Sweden write fraction on paper as $\frac{2}{3}$), whereas the $^{2}/_{3}$ notation was used in the game. The latter notation is introduced in the beginning of the story.
Inefficient order of content	We optimised the story so that prerequisite information is given before each challenge, and the story snippets form a logical flow.
Too easy challenges	We added more AR rods to some challenges in order to increase their difficulty.
Lack of visual information in hints	We implemented a hint system for each challenge to support text and image (e.g. an example comprising two dimensional rods and an explanation).
Need for an introduction of the concept of fractions	The AR rods playground was created to allow players to experiment with fractions, for example by matching the length of a particular rod with other rods.
Need for scaffolding	We used the chat (story, hints) to provide scaffolding information (e.g. pictures of the rods, examples) to the player.
Difficult texts for the target user	We explained some texts in an easier way for elementary school students (e.g. explained “equals the same as” as “how many do you need to build as long as...”).
Similar feedback on all challenges	We customised the positive feedback given for each challenge to explain the solution.

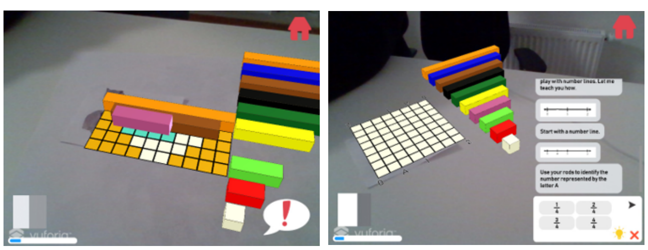
The completed Tales & Fractions was evaluated using a mixed-method strategy at two elementary schools in Sweden with 56 students (27 males, 29 females) with an average age of 11. The evaluation results showed good reception among the participants, but they also pointed out several points of improvement, such as technical bugs, difficulty imbalance in some tasks, and issues with user interaction. Furthermore, the video playback feature was not used in the game due to lack of

TABLE III: Issues & solutions regarding UI and optimisation

Issue	Solution
Cumbersome UI layout	We divided the layout into distinct groups: hint, feedback, the player's answer, dialogue, game progress, challenges and AR (in its own view).
Random marker image	We designed a new marker image based on the leopards that was more in line with the overall game design.
No localisation	UI texts and the story were prepared in English and in Swedish.
Target devices	We changed the build platform and project settings from PC to tablet device.
Overused resources	We lowered the textures' quality, and changed the shadow, light and rendering configurations.
Camera overuse	The game activates the camera only when the AR view is opened.

TABLE IV: Issues & solutions regarding AR

Issue	Solution
Manipulating the rods was not intuitive.	A visible "placement zone (PZ)" was added to the AR view (Fig. 6a).
The rods had physics to make them more realistic, but aligning them correctly was difficult.	The rods' orientation was fixed and collisions between the rods were disabled to help placing them on the PZ (Fig. 6).
PZ did not give clear feedback on the space taken when the rods were moved on top of it.	Blue grid highlighting was added to the PZ (Fig. 6a).
PZ's size was fixed and irrelevant of the number of rods.	PZ's size automatically adjusts to the challenge at hand.
Fixed number of AR rods	Adding and removing rods was allowed to enable free experimentation by the player.
Some of the tasks required more information to be shown on the AR playground.	A custom AR playground was added to show the required information near the PZ (Fig. 6b).



(a) (b)

Fig. 6: The two types of AR playgrounds

time that preparing copyright-free video content of sufficient quality would require. Further elaboration on the evaluation results is subject to a follow-up publication.

V. Discussion

Throughout the two-phase development process of Tales & Fractions, we faced many issues that we resolved by means of multidisciplinary team of experts. Not only the issues from the second phase but also some of issues from the first phase were solved by collecting regular feedback and exchanging ideas in regular meetings among the experts. The description of the development process and the solutions proposed in Tables II–IV can be useful to educational story-based AR game developers as a means to avoid common pitfalls and to increase the engagement value of the end result. Similarly, the game's novel concept may motivate educational game researchers and educators to create and adopt educational games that are based on a strong story instead of a weak excuse of a narration that, based on our literature review, is more prevalent in educational games, and especially those that use AR.

Our analysis of the multidisciplinary development process, the structure of the development team (Fig. 4) and the roles of the expert groups can be related to the TPACK model [33] which describes how an educational technology can be successfully integrated into an educational setting such as a classroom. In simple terms, the TPACK model suggests that an educator should have adequate *technological* knowledge, *pedagogical* knowledge and *content* knowledge in order to effectively utilise an educational technology in the classroom. For the development of an educational game, we cannot expect that all this knowledge is with a single person. Therefore, in our multidisciplinary team, technological knowledge is represented by programmers, whereas pedagogical and content knowledge are covered by educators. Yet there are differences between the TPACK model and our multidisciplinary workflow. For example, our team also involved artists & designers. By drawing these parallels between the TPACK model and our multidisciplinary workflow, we pose the following research questions: (i) to what extent can the proposed multidisciplinary development process influence the successful integration of the story-based game into a learning environment?, and (ii) what changes need to be made to the TPACK model so that it can also support the multidisciplinary development process? Answering these questions, and analysing the correspondence between the multidisciplinary workflow and the TPACK model, are to be investigated in future research. This will consequently enable mapping of the roles of each expert group and the intersection parts in Figure 4 to the TPACK model for providing a starting point that can be considered by story-based educational game developers and educators.

VI. Conclusion

We described a multidisciplinary project conducted by computer scientists, artists, designers and pedagogical experts to create a novel story-based AR mobile game on tablets. The game was aimed to elementary school students, thus the UI, story, and learning content were designed carefully based on target players' abilities in order to facilitate achieving the flow state [34] during gameplay. We gathered a group of experts in different fields and employed an adapted version of the Scrum agile software development method to establish an iterative development process based on continuous communication and feedback loops among the experts. The end result – Tales & Fractions – has a strong focus on story, which we found to be lacking in previous educational AR games.

Tales & Fractions was designed based on the identified affordances of storytelling, AR and math manipulatives with a goal of strengthening the following four motivators that have been found in engaging educational games: (i) fantasy through storytelling, (ii) technology through the use of tablets and AR, (iii) challenge through fraction challenges, and (iv) relations through multiplayer experience when the tablet is shared by two or more players. We anticipate that the game may have additional motivators that are yet to be identified in a follow-up evaluation study that we have planned. Moreover, the pedagogical and motivational effects of the combination of the AR manipulatives and the strong story focus form an interesting research avenue for us to pursue in the future.

We expect that the results of this study provide valuable insights to educational story-based AR game developers by introducing issues and possible methods to obtain solutions.

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