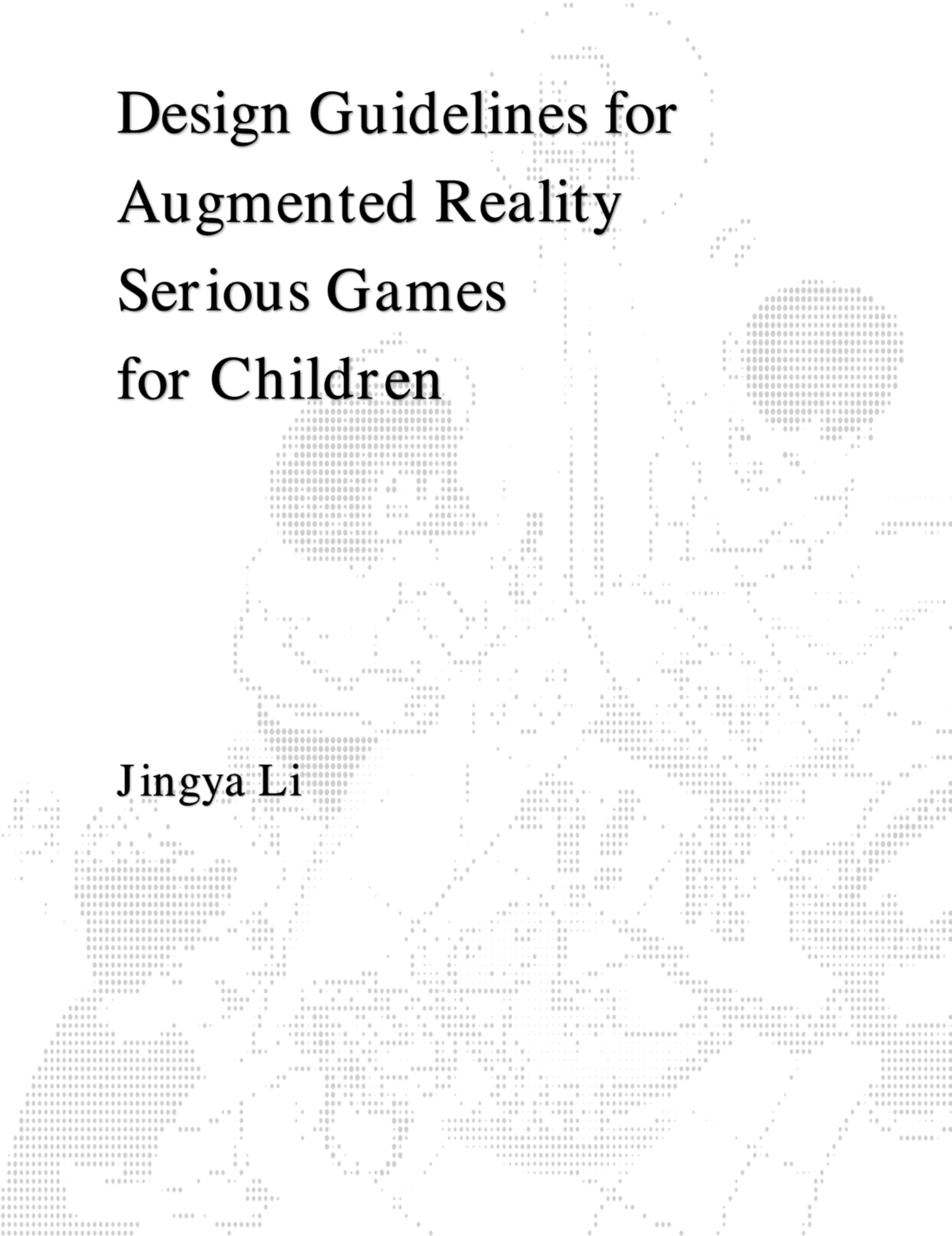
Design Guidelines for Augmented Reality Serious Games for Children

Jingya Li



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Design Guidelines for Augmented Reality Serious Games for Children

THESIS

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door

Jingya Li

geboren te Beijing, China

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Het onderzoek of ontwerp dat in dit thesis wordt beschreven is uitgevoerd in overeenstemming met de TU/e Gedragscode Wetenschapsbeoefening.

Summary

Today's children are born in a world with rapid growth of multimedia technologies and are used to handling all kinds of digital devices, they furthermore appear to be attracted to digital games and spend a lot of time with them. Consequently, digital games for educational purposes, also known as serious games, have become an increasingly important method for learning and instruction. However, empirical evidence of serious games being more motivating is still lacking, and as many serious games focus on single-player instruction, serious gameplay can sometimes be a physically and socially isolating experience.

Recently AR technology has become an emerging solution to positively impact learning and motivation, providing unique benefits of visualization and interaction between users and digital content embedded within the physical environment. In this research, we designed, prototyped, evaluated, and iterated multiple AR serious games as probes to investigate the main research objective, which was to find:

Design recommendations for AR serious games to positively influence the learning motivation and experience of elementary school children.

Our research follows a research through design method. We integrated the Self-determination theory and Playful Experience framework with the technical opportunities of AR and game design mechanics. We formulated the main research question as:

How to design AR serious games based on notions of perceived competence, relatedness, and autonomy in Self-determination theory to enhance children's learning motivation and experience?

To answer the research question, we divided our research into four main studies, each including game development and a formal experiment with users. The second, third, and fourth study each addresses one of the three components of SDT, and each study builds upon the insights gathered in the previous.

In the first study, we explored the game concepts by conducting participatory design sessions with elementary school children and a cross-culture study with 38 participants aged 7-8 from the Netherlands and China. Through this study, we came up with our basic game concepts and concluded design insights regarding the motivational effects of AR and the cultural differences.

In the second study, we designed a new game based on the design insights from the first study and notions of perceived competence in SDT, investigating how children react to two different types of interactions and two different types of feedback mechanics when performing exercises in AR serious game with 32 participants aged 7-8.

Then, we designed and implemented a new game considering the design implications obtained from the first and second study and notions of perceived relatedness derived from SDT, to scrutinize the effect of social interactions in AR serious games on children. We conducted another participatory design session and designed a game with collaboration and competition elements variations, and conducted a user study with 28 participants aged around 9.

Lastly, we designed an AR game inspired by notions of perceived autonomy with four different versions, once again based on the results from the previous studies, and tested pathways to immerse children to explore and play in an AR fantasy world. We conducted an experiment with 81 participants aged around 8.

Generally, this research explored the concepts, prototypes, and experiments of incorporating AR with serious games and found great potential to improve the learning motivation and social interactions for elementary school children. We realized multiple AR prototypes inspired by SDT and generalized a set of design guidelines using examples, which are intended to help future related designs in AR serious games.

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ONE

INTRODUCTION

Bob is an elementary school student in group 5 from the Netherlands. He has little homework to do, except for some basic exercises in a textbook. He likes playing digital games and plays games on the computer or iPad for about 1 hour per day and longer on the weekends. He plays by himself, sometimes he discusses the game he plays with his classmates at school.

Xiao is a 3rd-grade elementary school student from China. She spends a lot of time doing her homework every day, especially on mathematics. Her parents supervise her in finishing her homework, and then her teacher will check her homework the second day at school. Her parents think that she doesn't enjoy doing her homework because she easily gets distracted and can't concentrate for long periods of time. She likes to chat with her friends online and has a virtual pet, which she frequently wants to check on.

We wonder if there is a solution, which Bob and Xiao both think is interesting and can play together with their friends, and increases Xiao's motivation to finish her homework, as well as gives Bob opportunities to practice the things he has learned from school in the way he likes. If there is a solution, what would it be like?

Chapter 1: Introduction

1.1 Children in the Digital World

Today’s children were born in a world with a rapid growth of multimedia technologies and are used to handling all kinds of digital devices. According to the report on children’s usage of digital media conducted by the Common Sense Media in 2017, nearly all (98%) children in the U.S. age 8 and under have some types of mobile devices in their home. 95% of families with children at this age have a smartphone now. The number of children that have a smartphone is growing from 41% in 2011, 63% in 2013, to 95% in 2017. The number of children on tablets is also growing to 42%, up from 7% in 2013 and less than 1% in 2011.

Not only the number of digital devices is increasing in families with children, how children are using these devices has also shifted considerably with an increasing amount of time spent on them. They appear to be attracted to digital devices more than their previous generation and spend a lot of time browsing on and playing with them (Girard, Ecalle, & Magnan, 2013). The average amount of time spent with mobile devices each day has tripled from 2011 to 2017, going from 5 minutes a day to 48 minutes a day (Common Sense Media, 2017).

When children grow up (8 to 12 years old), they spend more time on digital devices: 4 hours and 44 minutes per day (Common Sense Media, 2019). Some of them even spend more than 8 hours per day with the screen. They use digital media for different activities, such as gaming, using social media, and video-chatting.

The increasing usage of digital devices of children raises concerns. According to the report, 72% of children aged 8 to 12 say that their parents have concerns about how much time they spend with digital media and the type of content they use. Besides, many children multitask with media while doing their homework (Common Sense Media, 2017). For younger children, excess screen time may also have an impact on their eyes (Shih and Killeen, 2020). The World Health

Organization recommends limiting the time with digital devices per day for children and encouraging the 20-second break for every 20 minutes (Shih and Killeen, 2020).

Parents who are already worried about the time their children spend on digital games and social media could become more concerned since the start of the COVID-19 pandemic (UNICEF, 2020). According to the report from UNICEF (2020), almost 90% of countries have implemented remote learning policy and students spend more time with digital devices to connect to the outside world now, which may affect how they play, learn, and interact with each other profoundly.

To improve the experience of children using digital technologies, more attention should be paid to what children do online, the content they encounter, and their network environment (UNICEF, 2020). The report also recommends children staying in touch with friends with video games and social media, which can offer connectedness and entertainment: "*the right amount of screen time seems to be optimal for children*".

Digital devices have become an enormous presence in children's lives, as well as a huge claim on their time and attention. Children spend all this time with digital technologies in their free time and then go back to analog books in the classroom, which is not attractive and does not connect to the outside world. Since it is already an important part of their life, learning can be contextualized in the digital world to better fit their interests. Therefore, it is an opportunity here to better utilize the technologies to facilitate education and balance the learning and entertainment.

At the same time, we do see a trend of digital instructional materials slowly being introduced in the 21st century classrooms. In the 21st century environment, teachers increasingly rely on digital instructional materials at school for subjects such as mathematics (Pepin *et al.*, 2019). School textbooks need to be connected with technology too (Pepin *et al.*, 2019). Digital instructional materials have noted potential to embed assessment, and to provide different kinds of feedback and performance data to students, teachers, and parents, as well as to offer different ways of providing difficulty, through choice or adaptation, to enhance customizability (Choppin *et al.*, 2014; Pepin *et al.*, 2017). In the meantime, including traditional textbooks in elementary school has also shown significant positive effects in students' arithmetic achievement (Sievert *et al.*, 2019). The traditional and digital instructional materials have shown different advantages in terms of academic effect, suggesting that the best textbook presentation of the future should combine both tangible paper identity and digital components (Usiskin, 2018).

1.2 Current Solutions

1.2.1 Serious Games

The high level of motivation and engagement with multimedia technologies and digital games has the potential to enhance the learning experience (Boot *et al.*, 2008; Tanes and Cemalcilar, 2010; Wrzesien and Raya, 2010). Consequently, digital games focusing on educational purposes, often referred to as serious games or game-based learning (Wouters and van Oostendorp, 2013), have become an increasingly important method in learning (Girard, Ecalle, & Magnan, 2013; Miller *et al.*, 2011; Wouters *et al.*, 2013). Three decades of development and research have found ample evidence that serious games have potential as instructional materials, accompanied with design guidelines on how to make a serious game more efficacious (van der Spek *et al.*, 2014; Wouters *et al.*, 2013). However, empirical evidence for serious games to be more motivating in general than conventional instruction might be lacking (Wouters *et al.*, 2013). Serious games can be a supporting factor in the learning process, but might not be more motivating than textbooks (Stege, van Lankveld, & Spronck, 2011). More research needs to be done on how serious games should be designed to be engaging, in particular systematic value-added research as was done previously for the learning efficacy of serious games (Mayer, 2019). Contextual decisions can also influence these results, and for instance, previous studies have identified issues with successfully integrating serious games in the classroom. Some games are not designed to fit into standard classroom hours and the computers to play the games on are often located in another room (Tüzün, 2007), making it more difficult to integrate games with existing instructional materials (Wouters *et al.*, 2013), such as textbooks. Furthermore, as many serious games focus on single-player instruction, children do not always have the chance to experience social interactions with traditional serious games (Michaelis and Mutlu, 2019), while social interactions in an educational context can improve children's learning experience and learning performance, giving them opportunities to exchange ideas, share knowledge, and perceive a sense of social involvement (Bergin, 2016; Johnson and Johnson, 1986; Michaelis and Mutlu, 2019; Phon *et al.*, 2014; Robnett and Leaper, 2013; Wouters *et al.*, 2013).

1.2.2 AR Technology

"One day, we believe this kind of immersive, augmented reality will become a part of daily life for billions of people."

— Mark Zuckerberg, Founder and CEO of Facebook

Augmented reality (AR) enables the user to see the real world with virtual objects on top of it (Azuma, 1997). It is an emerging technology that enhances the interaction between users and digital content embedded within the physical environment (Azuma, 1997; Dunleavy and Dede, 2014). There are many potential benefits that AR can bring to children, such as enhanced entertainment (Ibáñez *et al.*, 2014; Lu and Liu, 2015) and advancing education (Kerawalla *et al.*, 2006; Shelton and Hedley, 2003). Educational researchers have recognized the new possibilities for teaching and learning with AR technology increasingly (Wu *et al.*, 2013). Wu *et al.* (2013) identified that AR could enhance children's learning experience by using 3D synthetic objects that children can interact with. AR integrates the sight of virtual objects with the feeling of physical objects (Arvanitis *et al.*, 2009; Kaufmann, 2003). In addition, AR also enables the visualization of invisible concepts or events by superimposing the virtual content onto the physical objects (Dunleavy *et al.*, 2009). Secondly, prior research suggests that AR interfaces can support collaborative activities (Bhattacharyya *et al.*, 2019). AR has shown great capacity to enhance social interactions because children could communicate face-to-face as well as via the digital device (Birchfield and Megowan-Romanowics, 2009). Thirdly, AR offers immersive experiences for users (Bronack, 2011) in which the real and the virtual world are blended (Klopfer and Sheldon, 2010), and their interactions and engagement are augmented (Dunleavy, Dede, & Mitchell, 2009). The augmented space could give learners a sense of participating in a realistic environment (Dede, 2009). AR environments could improve students' learning motivation and learning interest, which in turn may help them develop better skills and gain more accurate knowledge (Sotiriou and Bogner, 2008).

In 2016, the launch of an AR game, *Pokémon Go*, has become one of the most popular examples of applying AR technology (Landi, 2016). In *Pokémon Go*, GPS is used to match the location of the player in the real world with the virtual world (Paavilainen *et al.*, 2017). When Pokémon creatures appear in the virtual world, AR is used to overlay the Pokémon on the real-world viewed through a mobile camera (Figure 1.1).

The high level of motivation and engagement of Pokémon Go has brought worldwide interest in the opportunities AR games can offer (Rauschnabel, Rossmann, & Dieck, 2017). The unique experience that AR affords, such as the interaction with reality, the requirement of moving around, and the social interaction, differentiates it from traditional video and online games (Yang and Liu, 2017).

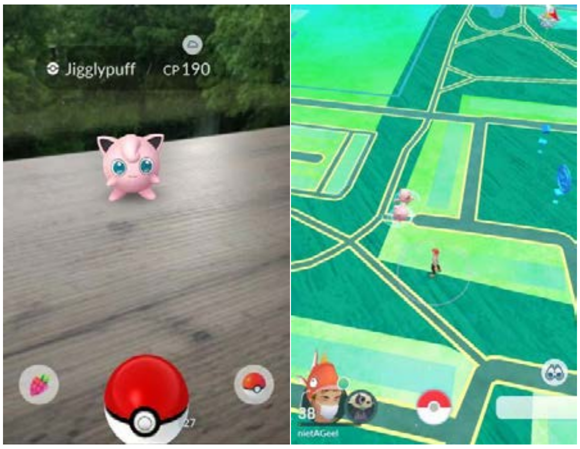

Figure 1.1 In-game scenes from Pokémon Go.

1.2.3 AR Serious Games

As mentioned above, issues were identified with serious games. In the current school environments, it is not easy to implement a strategy to involve both paper and digital media (Usiskin, 2018). AR technology could be a good way to solve these problems. Furthermore, motivation plays a critical role in designing effective educational applications for children (Malone and Lepper, 1987). In the context of Child-Computer Interaction (CCI), AR technology has been applied to support a wide range of play-and-learn activities for children (Malinverni *et al.*, 2018). Therefore, with the engaging and motivating experience AR can offer, the past few years have witnessed growing popularity in the research interest for AR serious games in the educational sector (Atwood-Blaine and Huffman, 2017; Fotaris *et al.*, 2017; Furio *et al.*, 2015; Radu, 2014; Radu, MacIntyre, & Lourenco, 2016). Integrating AR with games could take the advantages of serious games and combine them with traditional learning materials, providing benefits of unique visualization and interaction possibilities (Kaufmann, 2003), as well as supporting social interaction (Bhattacharyya, 2019; Billinghurst and Duenser, 2012), maintaining high levels of motivation and influencing children's learning experience positively (Campos, Pessanha, & Jorge, 2011; Jesionkowska, Wild, &

Deval, 2000; Miller *et al.*, 2011). Previous studies have noted significantly higher motivation with AR games over non-AR games. Additionally, AR-based learning games have shown the potential to positively influence students' intrinsic motivation for science learning (Sotiriou and Bogner, 2008). Squire and Klopfer (2008) also suggested that AR-based games could connect students' prior knowledge to the physical world and engage students in the learning content and practices. The increased motivation and active engagement in AR games can potentially translate to compelling educational media and make learning more enjoyable and immersive for children (Fotaris et al., 2017).

To achieve the potential benefits of AR serious games, we need to understand children's reactions to them and design the AR serious games appropriately for children. AR and non-AR games are different, because AR introduces virtual elements into physical environments and children can see the real world in both the screen display and the real space. Therefore, existing guidelines developed for non-AR settings, such as for digital serious games, are likely to have limited applicability to AR (Bujak *et al.*, 2013, Radu, 2014). In addition, while previous studies have applied game-design mechanics to learning processes in the design of (digital) serious games, a similar systematic and empirically tested approach towards the design of AR-based learning is still missing (Antonaci, Klemke, & Specht, 2015). The question of how one should design an AR serious game to stimulate learning motivation therefore remains largely unanswered and requires further exploration (Hwang *et al.*, 2016). Having a deeper understanding of specific game elements could help designers make better design choices to amplify the advantages of AR to support students' play and learning experience (Dunleavy, Dede, & Mitchell, 2009).

1.3 Research Objectives

1.3.1 Main Research Objective

The purpose of our research is twofold: to gain a deeper understanding of the design choices in AR serious games and produce generalized and abstract knowledge that others can use, and to create a specific solution to improve the learning experience for children and make the traditional learning materials more fun (Stappers and Giaccardi, 2017). To reach these goals, we included target users in the design process from the very beginning to design with us for the concepts of the game prototypes. Then we iterated our game prototypes based on Self-determination theory (SDT), aimed to empirically and systematically test different game design principles on learning motivation and come to a set of guidelines for AR serious game design.

"The designing act of creating prototypes is in itself a potential generator of knowledge (if only its insights do not disappear into the prototype, but are fed back into the disciplinary and cross-disciplinary platforms that can fit these insights into the growth of theory)."

— Stappers, 2007, pp.87

Throughout this thesis, we describe the development of a collection of games collectively called *See Me Roar*, an acronym for Self-determination Enhanced Engagement for Math Education Relying On Augmented Reality. We designed the game in a series of prototypes, each of which addresses one aspect of SDT. Our research process included: 1) a concept exploration of the basic prototype and a cross-cultural user study; 2) the design of a Feeling-of-Competence-inspired prototype and a user test to understand how different interaction types and feedback types impact motivation; 3) the design of a Feeling-of-Relatedness-inspired prototype and a user test to find out how children perceive the social interactions within collaboration and competition in AR serious games and its effect on motivation; 4) and the design of a Feeling-of-Autonomy-inspired prototype and a user test to figure out the effects of providing opportunities for exploration and elements of fantasy on motivation. We designed, prototyped, evaluated, and iterated multiple AR serious games to investigate:

Design recommendations for AR serious games to positively influence the learning motivation and experience of elementary school children.

1.3.2 Research Approach

Situated learning and constructivist learning are two educational psychology paradigms that are frequently applied to support the ideas of AR enhancing the learning experience (e.g., Dunleavy and Dede, 2014). Situated learning holds the claim that all learning should ideally take place in the same context in which it is applied (Lave and Wenger, 1991). Similarly, constructivist learning also posits that learning tasks should be embedded within relevant environments (Bruner, 1966; Vygotsky, 1978). In addition, it assumes that children construct their own knowledge based on their prior experience and knowledge (Bruner, 1966; Vygotsky, 1978). AR aligns well with these two learning paradigms since it positions the learner within the real-world physical and social environment (Dunleavy and Dede, 2014). Since we are researching the design of AR serious games, our games should be seen as embedded in these educational paradigms. However, as our research was primarily motivated to understand how to make these games more fun, and not on improving their learning efficacy (because many such studies already exist in the context of serious games), the pedagogical approach was not a major focus in the development and analysis of the games.

Flow theory is an influential theory in the research of intrinsic motivation and engaging experience (Nakamura and Csikszentmihalyi, 2014), which has been popular among Human-Computer Interaction (HCI) game researchers (Tyack and Mekler, 2020). However, the notion of flow focuses on the individual level, where being in “flow”, one enters a state characterized by a loss of reflective self-consciousness, such as the loss of awareness of oneself as a social actor (Nakamura and Csikszentmihalyi, 2014). In addition, a lack of reflective self-consciousness could negatively impact learning. In our research, we also want to figure out how to offer social opportunities to connect children. Therefore, in our study, we applied the Self-determination theory (SDT) (Deci and Ryan, 1985).

SDT is a well-established theoretical framework for intrinsic motivation research in digital games accompanied with empirical support (Przybylski, Rigby, & Ryan, 2010), which has been used to study the motivational appeal of digital games (Ryan and Deci, 2017; Ryan, Rigby, & Przybylski, 2006), inform gameful design (Deterding, 2015; Rigby, 2014), and evaluate the playful experience (Johnson, Gardner, & Perry, 2018), According to Tyack and Mekler (2020), the original papers on SDT and games (Przybylski, Rigby, & Ryan, 2010; Ryan, Rigby, & Przybylski, 2006) have been cited over 3000 times on Google Scholar.

SDT includes three basic psychological needs for human well-being, including the need for competence, the need for relatedness, and the need for autonomy (Deci and Ryan, 2002; Ryan, 1995; Ryan and Deci, 2000a; Ryan, Rigby, & Przybylski, 2006). These three psychological needs are proven to be positively associated with intrinsic motivation and independently predict a higher enjoyment level and desire for future game play (Prybylski, Rigby, & Ryan, 2010; Ryan, Rigby, and Przybylski, 2006). Intrinsic motivation is defined as "doing something because it is inherently interesting or enjoyable" (Ryan and Deci, 2000a, pp.55), which leads to enhanced creativity and improved learning outcomes (Ryan, 1995; Ryan and Deci, 2000a, 2000b).

Evidence has shown that the intrinsic motivation is facilitated when the three psychological needs of human motivation are satisfied (Kappen, Mirza-Babaei, & Nacke, 2017) and the needs fit well in an educational environment (Deen and Schouten, 2011). Tyack and Mekler (2020) argued that the extent to which SDT has informed HCI games research remains unclear, little has been done on the ways in which HCI game researchers have applied and engaged with the theory. However, we noticed work to cite SDT in serious games. Deen and Schouten (2011) proposed an approach to design serious game based on identified regulations to satisfy the three basic needs: for competence with scaffolded learning difficulty and progressive feedback, for autonomy by providing the opportunity to make significant decisions and to enable various playing styles, and to relatedness by embedding of the game in a social environment. Lamprinou and Paraskeva (2015) designed and evaluated a gamified scenario for primary education aimed to increase intrinsic motivation based on SDT. According to the study, the game elements such as challenges, progression bars, badges, points, leaderboards, levels, awards, and time could be used to promote the feeling of competence; immediate feedback, meaningful choices, and a personalized environment where children have their own role could increase the feeling of autonomy; and collaboration between teams, competitions, leaderboards, ranking, as well as role-playing, avatars, storytelling, etc., could increase the feeling of relatedness (Lamprinou and Paraskeva, 2015). At the start of our research, how to translate design knowledge on how to apply SDT principles in the design of AR-specific serious games was still somewhat new. We hope that our research can contribute to that body of knowledge.

To address our research goal, we proposed a structured framework based on SDT and furthermore incorporated the Playful Experience (PLEX) framework (Arrasvuori, Boberg, & Korhonen, 2010; Korhonen, Montola, & Arrasvuori, 2009).

The PLEX framework summarizes categories that users might experience during game play (Korhonen, Montola, & Arrasvuori, 2009). The PLEX framework identifies 22 categories of playful experiences based on previous theoretical work on pleasurable experiences, elements of play, and reasons why people play, which has been applied as a basis for design-related activities and concept development (Korhonen, Montola, & Arrasvuori, 2009). After a review of the categories, some of them were considered not really suitable for educational games for children (e.g. cruelty, eroticism, suffering) while others would be suitable for some learning domains but not others (e.g. humor, nurture, expression). As we wanted to find guidelines that were generically applicable to improve motivation in AR serious games, as well as to keep the scope manageable, we landed on the following 6 categories: challenge, competition, completion, exploration, fantasy, and fellowship.

The first step of our research approach was to map the suitable PLEX framework items to corresponding SDT needs based on the meaning and explanation of each psychological need and the definition of each playful category: the playful experience of challenge and completion were mapped to the need for competence; The playful experience of competition and fellowship were mapped to the need for relatedness; The playful experience of exploration and fantasy were mapped to the need for autonomy (Deci and Ryan, 2002; Ryan, 1995; Ryan and Deci, 2000a; Ryan, Rigby, & Przybylski, 2006). See Figure 1.2. Here we give a sneak preview of the game design so this chapter is easier to read, while the detailed game design and how we elaborated the current framework with AR features filled in will be found in the chapters later.

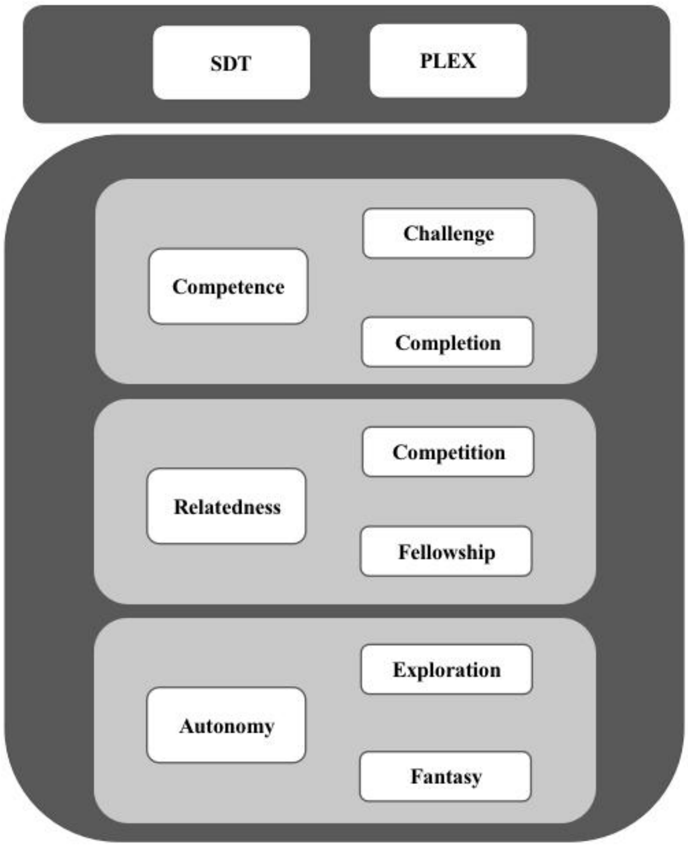

Figure 1.2 Structured framework based on SDT and PLEX.

- Competence

Competence within SDT is the need for challenge and feedback as a feeling of completion (Deci, Koestner, & Ryan, 1999; Ryan and Deci, 2000a, 2000b; Ryan, Rigby, & Przybylski, 2006). Activities such as acquiring new knowledge, being challenged in an optimal way, or receiving positive feedback, can enhance the feeling of competence (Ryan and Deci, 2000a, 2000b; Ryan, Rigby, & Przybylski, 2006).

  – Challenge: In the PLEX framework, challenge is described as testing abilities in a demanding task.
  – Completion: In the PLEX framework, completion refers to finishing a major task, closure.

- Relatedness

The feeling of relatedness within SDT concerns the experience of feeling connected with other people (Deci, Koestner, & Ryan, 1999; Ryan and Deci, 2000a, 2000b; Ryan, Rigby, & Przybylski, 2006).

  – Competition: In the PLEX framework, competition is defined as contest with oneself or an opponent.
  – Fellowship: In the PLEX framework, fellowship is described as friendship, communality or intimacy.

- Autonomy

The feeling of autonomy within SDT refers to the feeling of one's behaviors as self-determined rather than controlled by others (Deci, Koestner, & Ryan, 1999; Ryan and Deci, 2000a, 2000b; Ryan, Rigby, & Przybylski, 2006). The experience of autonomy is high when the task is done for personal interests or values (Su and Reeve, 2011).

  – Exploration: In the PLEX framework, exploration is defined as investigating an object or situation.
  – Fantasy: In the PLEX framework, fantasy refers to an imagined experience.

A more detailed argumentation for why these elements from the PLEX framework were selected to map to competence, relatedness and autonomy, can be found in the individual experiment chapters.

1.3.3 Research Questions

While we have a general theoretical framework to guide our design, we are going to explicate and position it in the context of AR serious games. Therefore, we further concretized the main research goal into three research questions based on the main research objective and the proposed framework:

How to design AR serious games based on notions of perceived competence, relatedness, and autonomy in Self-determination theory to enhance children's learning motivation and experience?

RQ1. How to incorporate AR-specific elements in serious games based on notions of perceived competence in Self-determination theory to enhance children's learning motivation and experience?

- **1.1** How can we integrate different types of challenges in AR serious games for children, and which of these types work better?
- **1.2** How can we integrate different types of completion in AR serious games for children, and which of these types work better?

RQ2. How to amplify the advantages of social interactions in AR serious games based on notions of perceived relatedness in Self-determination theory to enhance children's learning motivation and experience?

- **2.1** Which types of social interactions in terms of competition and fellowship should we integrate into AR serious games for children?
- **2.2** How do children perceive their social interactions in terms of competition and fellowship in AR serious games?

RQ3. How to apply game design mechanics to AR serious games based on notions of perceived autonomy in Self-determination theory to enhance children's learning motivation and experience?

- **3.1** What are the effects of providing children opportunities for exploration in terms of task choice in AR serious games?
- **3.2** What are the effects of providing children elements of fantasy in terms of game story in AR serious games?

1.4 Methodology

Our research follows a research through design method (Jonas, 2007; Koskinen *et al.*, 2011), where we develop the games and instructional designs based on the structured framework, and the base prototype is modified to include these new levels. According to the model proposed by Zimmerman, Forlizzi, & Evenson (2007), in the research through design approach, interaction design researchers integrate the models and theories from behavioral scientists (in our case SDT and PLEX) with technical opportunities demonstrated by engineers (in our case AR and game design mechanics). See Figure 1.3. We also involved our target users, elementary school children, from the start of our design process to design with us for the game concepts. Through this design and implementation process we seek to chart the design space of AR serious games, investigate questions regarding the influence of AR-specific elements, social interactions, and game design mechanics stimulating competence, relatedness, and autonomy on motivation and learning. Having a deeper and fuller understanding of the effects of AR specificities could help designers make suitable design choices and take advantage of their affordances to enhance the play-and-learn experience for children (Malinverni *et al.*, 2018).

A research through design approach can be beneficial in identifying opportunities for new technology or existing technology that will have the potential to significantly impact children's learning motivation and experience (Zimmerman, Forlizzi, & Evenson, 2007). The design artifacts and the design iterations and evaluations can contribute to improve theory and practice (Schouten, 2011). This type of design research provides researchers with inspiration and motivation for what we might build, as well as undertake problem framing that helps identify important gaps in behavioral theory and models (Zimmerman, Forlizzi, & Evenson, 2007).

"*In evaluating the performance and effect of the artifact situated in the world, design researchers can both discover unanticipated effects and provide a template for bridging the general aspects of the theory to a specific problem space, context of use, and set of target users*".

— Zimmerman, Forlizzi, & Evenson, 2007, pp.5

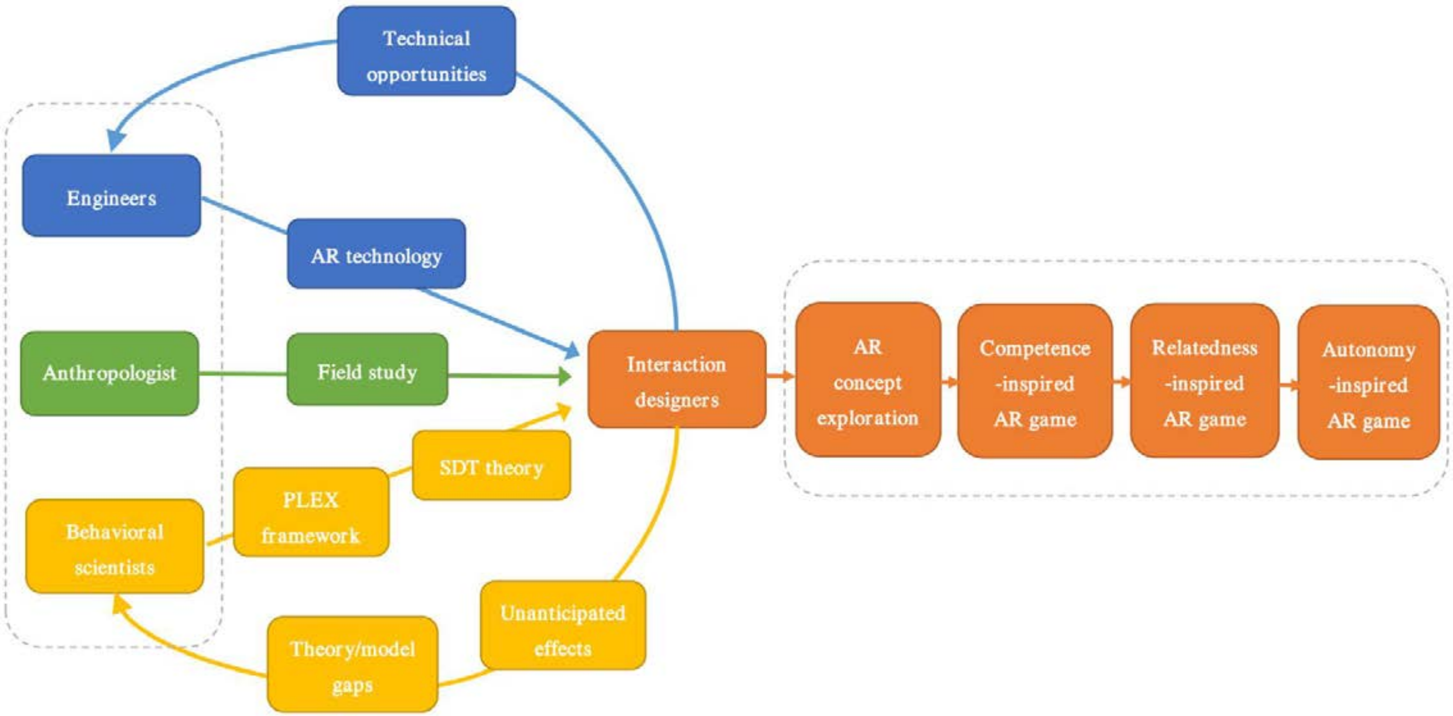

Figure 1.3 Design through research process inspired by Zimmerman, Forlizzi, & Evenson (2007).

1.5 Research Phases

Our research is divided into four phases, where each phase, usually called a "study", includes game development and a formal experiment with users. The second, third, and fourth study each addresses one of the three components of SDT. Each study builds upon the insights gathered in the previous.

To be more specific, in our first study, we explored the game concepts by conducting participatory design sessions with two elementary school children and a preliminary study with 38 participants (Mean age = 7.68) from the Netherlands and China. In this study, we were interested in 1) involving the target users from early on in the process and thereby increase the possibility that our game concepts would be accepted and liked by the age group; 2) coming up with initial design concepts of the AR game (namely See Me Roar); 3) understanding children's preferences between See Me Roar and traditional learning methods; 4) seeing if there is a difference in performance between See Me Roar and traditional learning methods; and 5) seeing if there are cultural differences among children from different cultural backgrounds. Through this study, we came up with our basic game concepts that hidden animals can be found in a school textbook waiting for children's help to solve mathematics problems. We concluded design insights regarding SDT with game concepts of interacting with a variety of animals. Then we continued to conduct the value-added studies with AR specific game design principles.

In the second study, we designed a new game based on the design insights from the first study and the feeling of competence in SDT, investigating how children react to two different interaction styles (screen-touch vs. tangible interaction) as well as two different feedback mechanics (2D progress bar vs. 3D progress map) when performing exercises in the AR game with 32 participants (Mean age = 7.78). Which types of interactions under AR settings are available and are promising to improve the motivation for children? Can we choose feedback mechanics such that they are compatible with the game's objective and if so, are they motivating indeed? These are questions we wanted to find answers answers to, in order to discern new design guidelines for AR serious games.

Then, we designed and implemented a new game considering the design implications obtained from the first and second study and relatedness principles derived from SDT, to scrutinize the effect of social interactions in our AR serious game on children. To come up with the concepts, we conducted another participatory design session with eight participants. After the participatory design session, we designed a game with collaboration and competition elements variations, and conducted a pilot study with 4 participants and a user study with 24 participants (Mean age = 9.04) in total in the process. In this way, we tried to find out in which version children would feel more related to each other. We also collected the ideas and suggestions from children in our previous studies through interviews. Do the children appreciate the virtual exploration on the physical book? How do children perceive the connection with each other in both the virtual world and the physical world? Are they willing to see richer content such as buildings and characters in the AR world as well? These are questions we hoped to answer in this study.

Lastly, we designed our autonomy-oriented game with four different versions, once again based on the results from the previous studies, and tested pathways to immerse children to explore and play in an AR fantasy world. We conducted a 2 (choice vs. no choice) x 2 (game story vs. no game story) experiment with 81 participants (Mean age = 8.82) to identify possible effects on motivation while performing maths exercises. Do children appreciate the freedom to explore the virtual and the real world? Can the AR fantasy world immerse children in the learning activity? In this study, we were curious to find out these answers.

1.6 Thesis Outline

Chapter 2 is the literature review, which elaborates the needs of learning motivation for elementary school children, existing design guidelines for AR serious games, current state of the art of AR serious games, and the theoretical framework of SDT and related game design mechanics.

Chapter 3 presents the exploration process of participatory design sessions and the game concepts of See Me Roar, as well as a cross-cultural study. We compared the AR serious games to a traditional paper exercise in China and the Netherlands, in order to find out if See Me Roar is preferred by children and if there are cultural differences. We generated insights based on SDT for the development of future versions of the game.

Chapter 4 introduces the design of competence-supportive elements in the AR serious games, which investigates how different interaction techniques and different feedback mechanics affect 7-8-year-old children's motivation in AR settings. Based on the results we identified recommendations for designers to stimulate competence in AR serious games to improve children's intrinsic learning motivation.

Chapter 5 presents the design of relatedness-supportive elements. We designed and developed the game concepts based on Chapter 4 and an exploration study as well as new participatory design sessions. We also conducted a user study to explore how children would behave and interact with each other in different game modes, competition and collaboration. Based on the results we identified recommendations for designers to develop relatedness in AR serious games to improve children's intrinsic learning motivation. Our findings extend the understanding of children's social patterns in both collaboration and competition conditions under AR settings.

Chapter 6 introduces the design of autonomy-supportive elements. We designed and developed the game concepts based on Chapter 4 and Chapter 5. We aimed to find out how we should design the fantasy and exploration in the AR game to improve children's learning motivation effectively.

In Chapter 7, the insights related to the research questions in this introduction and the reflections on the latest developments in AR serious games and research methodologies are summarized, and the limitations of this thesis and future research directions are presented. See Figure 1.4 for the research phases.

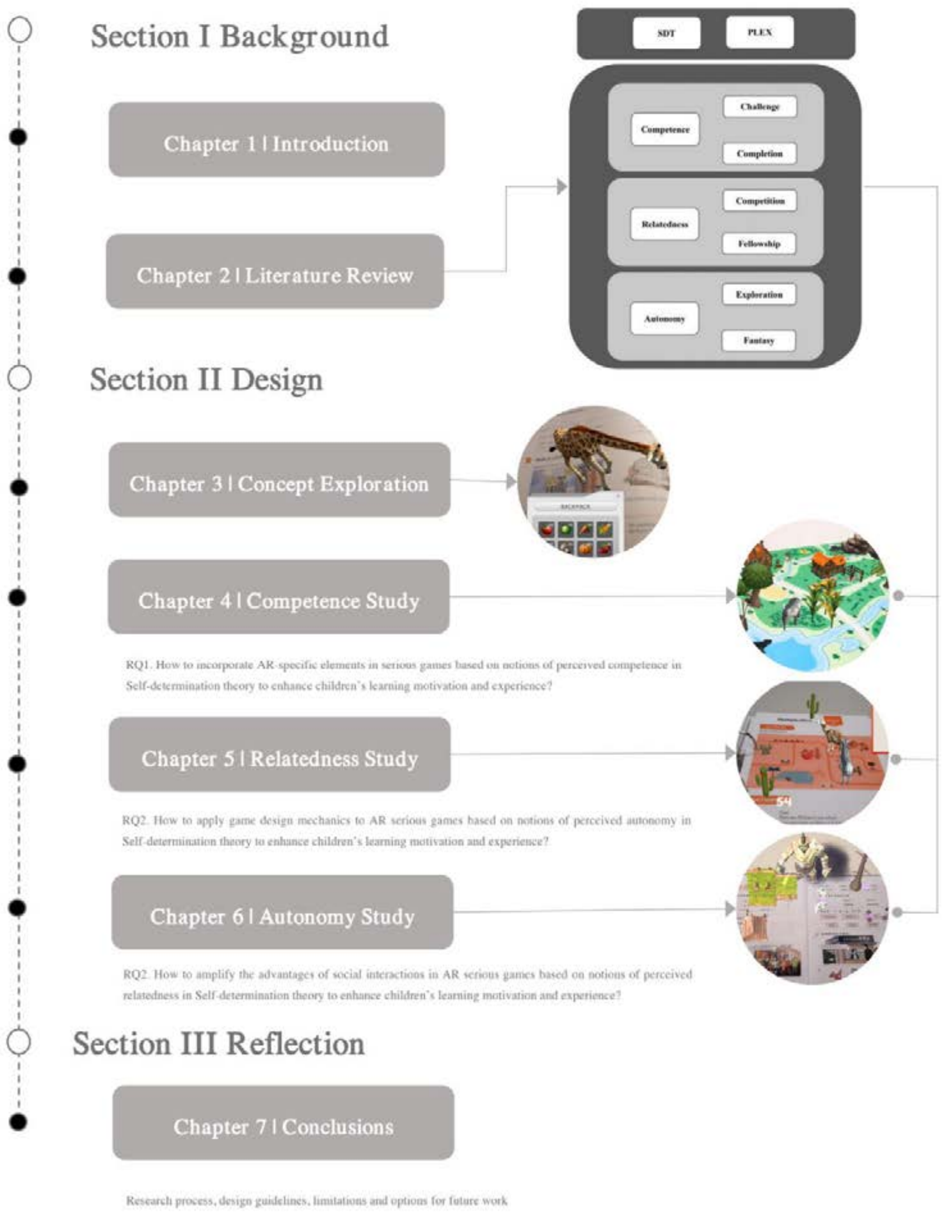

Figure 1.4 Research phases.

CHAPTER

TWO

LITERATURE REVIEW

Chapter 2: Literature Review[1]

In Chapter 1, we discussed the research background, research objectives, methodology, and thesis outline. In this chapter we describe four key aspects and related work that form the foundation of the work that has been developed in this thesis. These key aspects are listed below.

1) Motivation in AR serious games
2) Design guidelines for AR serious games
3) Current state of the art of AR serious games
4) Self-determination theory and playful experience framework

To begin with, it is necessary to further elaborate on the features of AR serious games and the reasons that they could have a positive impact on learning motivation. Despite the fact that research regarding AR-game motivation has a relatively short history (Zsila *et al.*, 2018), design guidelines have been proposed for usability, learning, and engagement before. It is essential to analyze and learn from these design guidelines. Following this, we need to understand the state of the art of AR serious games research, such as the learner groups, applied subjects, environments, mechanics, effects, etc., and identify the issues of existing research on AR serious games to find potential design space for our game. Moreover, we provide insights gained from SDT and match its three psychological needs to relevant game design mechanics in AR settings to build the structured framework guiding our research (See Figure 1.2 in Chapter 1).

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[1] **Based on:**

Li J., van der Spek E.D., Feijs L., Wang F., Hu J. (2017) Augmented Reality Games for Learning: A Literature Review. In *International Conference on Distributed, Ambient, and Pervasive Interactions* (pp. 612-626). Springer, Cham.

2.1 Motivation in AR Serious Games

"AR connects users to the people, locations and objects around them, rather than cutting them off from the surrounding environment."

— Azuma, 2017, pp.1

Azuma (2017) described AR as "*an immersive experience that superimposes virtual 3D objects upon a user's direct view of the surrounding real environment, generating the illusion that those virtual objects exist in that space*" (pp.1), which could enhance the user's perception of and interaction with the real world (Azuma, 1997, 2017). The past few years have witnessed growing popularity in the research interest for AR, since mobile devices, such as smartphones and tablets, have offered much easier and cheaper access to AR for users than before (Akçayır and Akçayır, 2017).

AR serious games have been reported as more motivating and engaging compared to traditional learning games for children in their learning experiences, stimulating their desire to learn, attracting their attention, and enhancing positive learning attitude (Ajit, Lucas, & Kanyan, 2021; Akçayır and Akçayır, 2017). The use of AR could improve children's learning efficiency and provide a more fun experience (Lee and Lee, 2008). Positive effects of AR technology on children's learning were also identified in the development of skills and knowledge, enhancement of learning experiences, and improvement of collaborative learning (Wu *et al.*, 2013).

With the advantages and positive outcomes of AR games in the educational domain, a growing number of studies have emerged in the past few years. For example, Chiang, Yang, & Hwang (2014) proposed an AR-based mobile system for conducting natural science inquiry-based learning activities for fourth-grade children. Their study indicated that children who learned with the AR system achieved significantly higher motivation compared to those who learned with a conventional inquiry-based mobile learning approach. Tobar-Muñoz, Baldiris, & Fabregat (2017) conducted a user study with an AR-based learning game for reading comprehension activities for children in the classroom. They found that children displayed greater motivation and interest in the activities with the AR game than the traditional approach. Lu and Liu (2015) integrated an AR-based digital learning game in a marine learning program for elementary school children. According to their study, the AR game raised the level of children's engagement and provided greater motivation than conventional marine education programs. Hung, Chen, & Huang (2017) examined the effect of applying AR as an alternative material to motivate children in learning about bacteria. Their study showed that children preferred the AR book to other learning materials such as 2D graphics and 3D physical objects. Vate-U-Lan (2012) reported on an AR pop-up book for elementary school language learning. According to the study, the AR book improved children's engagement during the learning activity. Children indicated that the AR book increased their desire to learn, which could be a stimulating educational resource. Muñoz-Cristóbal *et al.* (2014) presented an AR system for an across-spaces learning activity for elementary school children. The study found that AR helped children achieve their learning objectives and enhanced their learning engagement and motivation. Juan *et al.* (2010) presented an AR serious game for endangered animals using tangible cubes. Their study showed that children perceived more fun and enjoyed playing the AR game more than the non-AR game, even though they found the AR game was harder to use compared to the non-AR version.

In summary, previous studies have shown that AR serious games have the potential to enhance children's motivation during learning activities.

2.2 Design Guidelines of AR Serious Games

Since AR research is a growing topic, showing to have positive educational benefits (Ferrer *et al.*, 2013), several studies produced design guidelines for the design of AR in the education domain. Wetzel *et al.* (2008) presented a set of design guidelines that were obtained from their experience with three mixed reality games, including the location-based AR games, *Interference* and

TimeWarp, as well as a commercial AR card game, *The Eye of Judgment*. We can learn from the design guidelines of this study, such as to use a combination of real and virtual elements, to use the real-world location, to create sharable experiences, and to include various social elements. Yamabe and Nakajima (2013) introduced four AR case studies, namely *Augmented Reality Go*, *EmoPoker*, *Augmented Calligraphy*, and *AR Drum Kit*, finding that AR mode showed better interest/enjoyment, perceived competence, and value/usefulness than traditional learning style and PC mode. In their study, they discussed the importance of applying the real-time feedback, gaming features (e.g., points, goals), and physical interaction in AR applications. *Smartkuber* was a projection-based AR serious game for motivating cognitive screening for the elderly with dementia with tangible cubes (Boletsis and McCallum, 2017). In this study, the design implications regarding AR, interaction, test validity, and game motivation were obtained (e.g., "*the competition, reward, and feedback game mechanics can strongly motivate elderly players*").

Studies have also addressed the usability guidelines for AR applications. For example, AR-SEE (Ferrer *et al.*, 2013) was a mobile phone-based AR system for passive solar energy education. This study provided us insights into usability, motivation, and the impact on learning with AR serious games and derived guidelines for designing future AR serious games. For instance, despite AR serious games might reduce usability and increase task completion time compared to the desktop version, they could enhance participants' learning motivation.

Building on the analysis of existing AR games and applications, Radu and Maclntyre (2012) applied children's development psychology, such as children's skills in motor abilities, spatial cognition, attention, and logic and memory, to guide AR designs and to generate effective AR experiences for children aged 6-9 years old. For example, they classified two-hand coordination motions in AR systems into different difficulty groups: 1) both hands perform the same actions (e.g. Stuart, 2010), which could be performed by children as young as 6; 2) one hand is relatively stationary while the other moves (e.g., Entertainment, 2012; Radu *et al.*, 2011), which appears to be difficult for children aged 6; 3) interactions where both hands are performing independent actions (e.g., Andersen *et al.*, 2004; Zhou *et al.*, 2004). Radu and Maclntyre (2012) also claimed that AR games could be built to train motor coordination skills by challenging children to move both hands at the same time.

Some other studies also produced design guidelines for AR systems by analyzing existing research. For example, Ko *et al.* (2013) analyzed existing research and suggested new design guidelines by conducting a heuristic evaluation for three popularly AR applications, and then validated the usability guidelines with an improved AR prototype they developed. This study offered us useful principles such as "*make the users feel that they are controlling the system and the system is responding to their actions*". Antonaci *et al.* (2015) also proposed a research methodology to apply game design patterns to AR-based learning games for the training of professional education based on previous studies. The design patterns listed by the authors to take advantage of AR serious games included: "*synchronous communication*", "*object recognition*", etc. According to the authors, while game-based learning specifically proved to be helpful for learning, research is still needed to explore the potential of AR-based mobile learning games. The empirical evidence about how to design learning games using AR is especially missing (Antonaci *et al.*, 2015). Wasko (2013) created a set of guidelines for instructional AR systems, aiming to help designers understand the learning process of users and make reasonable decisions about how to use pictures and texts in their AR instructions, how to arrange content regarding to space and time, and how to avoid unnecessary information that may interfere learning. Similarly, Ardito *et al.* (2010) discussed the process for design guidelines of location-based mobile games for learning through analyzing existing papers and defining guidelines into five categories: game general design, control/flexibility, engagement, learning aspects, and social aspects. Santos *et al.* (2015) summarized existing guidelines for handled AR in other fields of application and provided their synthesis of these guidelines into five design guidelines, such as "*provide content controls*" and "*promote social interactions*". Another study (Poitras *et al.*, 2017) focused on examining the use of location-based AR systems to engage users in informal learning settings by evaluating current AR systems and drew recommendations based on the evaluation. More than that, Dunleavy (2014) reviewed literature and revealed three design principles when designing AR serious experiences: "*1) enable and then challenge; 2) drive by gamified story (fantasy); and 3) see the unseen (curiosity)*".

Overall, although an ample amount of research has been done on designing AR serious games and generating design guidelines for AR applications, research that focuses on the design guidelines for AR serious games and with empirical studies, especially for elementary school children, is still lacking. It is necessary to conduct research that focuses on systematically tested guidelines for AR serious games.

2.3 State of the Art of AR Serious Games

As can be seen above, the efficacy of AR learning games as an integrated concept is less well known, let alone what would be successful design strategies for AR serious games, and strategies to make them motivating especially. Therefore, we aimed to delve deeper into AR serious games, considering the state of the art of AR serious games, including their effects on motivation, learning achievement, social interactions, and the game design mechanics they have applied.

2.3.1 Learner Groups, Subjects, and Environments

Regarding the learner group, over 51% of AR serious games selected K-12 students as the target group (Akçayır and Akçayır, 2017). In 2017, we conducted a study investigating 27 papers from 2006 to 2016 focused on AR games for education and found that most of the AR learning games focused on elementary school students (31%) and middle school students (29%). High school students (20%) followed elementary school students and middle school students in popularity. According to a most recent study (Ajit, Lucas, & Kanyan, 2021), most AR articles were focusing on the K-12 level (72.72%). One potential explanation for this could be that AR serious games might have a positive influence on the younger audiences because they are more evocative and align better with the kind of games they are playing at home (Wojciechowski and Cellary, 2013). Ajit, Lucas, & Kanyan (2021) explained that K-12 students were the most preferred target groups possibly because learning tools such as AR could make it easier to concretize abstract concepts during the phase in elementary and secondary schools based on Piaget's developmental level (Kohler, 2014). In addition, we also found that the different levels of skills and abilities of students could influence their learning experience. For example, according to the study of Perry *et al.* (2008), when playing the same game, some students needed to read the text in the game with assistance, while students with a higher level of literacy skills could read the text and play by themselves. In another study, students from a higher educational level benefited more from the use of AR serious games than students from a lower educational level (Huizenga *et al.*, 2009). To better motivate students in their learning activities with AR games, one study also designed different learning content and story themes for elementary school students, middle school students, and high school students respectively (Squire and Jan, 2007).

Regarding the learning subjects, according to our own investigation (Li *et al.*, 2017), science and biology were highly focused subjects among all the subjects in previous AR studies (e.g., Bressler and Bodzin, 2013). This might be due to the affordance that AR technology offers in bringing the abstract and invisible concept of knowledge to life so that students can envision what is happening in the real-world environment (Bacca et al., 2014; Pellas et al., 2019). The study of physics, history, and art and design were second preferred subjects (e.g., Ayer, Messner, & Anumba, 2016; Ibáñez *et al.*, 2014; Squire and Jan, 2007). The real-time feature of AR enables students to receive feedback or see results immediately, which is favorable for subjects like art and design (Ayer *et al.*, 2016). According to a recent systematic review conducted by Pellas et al. (2019), the majority of the AR game-based studies from 2012 to 2017 applied Science, Technology, Engineering, and Mathematics (STEM) as the learning subjects. Table 2.1 shows the examples of different subjects of AR serious games.

Table 2.1 Subjects of AR serious games and location to use AR serious games.

Subject	Example of Research
Science and Biology	Atwood-Blaine and Hufman, 2017
Art and Design	Ayer *et al.*, 2016
Physics	Ismalina et al., 2018
History	Buchner and Zumbach, 2018
Mathematics	Cai et al., 2020
Chemistry	Chen and Liu, 2020
Literacy	Tosto et al., 2020
Culture	Eleftheria et al., 2013
Others	Pombo and Marques, 2020
Location	**Example of Research**
Classroom	Echeverría *et al.*, 2012
Outdoors	Pombo et al., 2017
No limits	Hsiao et al., 2016
Home	Lee and Lee, 2008
Others	Noreikis et al., 2019

Regarding the environments to use AR serious games, we saw significant preference from the viewed studies in using AR serious games outdoors and in the classrooms (Li *et al.*, 2017). See Table 2.1. These results align well with the latest reviews on class-context and field-trip as the most preferred educational context for AR serious games (Ajit, Lucas, & Kanyan, 2021; Ibáñez and Delgado-Kloos, 2018).

Playing outside is one of the advantages of AR serious games compared to other serious games, which may stimulate interest and excitement in students (Bressler and Bodzin, 2013). For example, existing studies for history learning often allowed students to explore the history of a certain spot using location-based feature (e.g., Dunleavy, Dede, & Mitchell, 2009; Harley et al., 2016). However, AR serious games for outdoor might face the technological challenges (e.g., localization accuracy, lightning conditions, etc.) and the pedagogical challenges (Ducasse, 2020). The safety issues should be considered as well. Children might come into dangerous situations, such as car accidents, when they pay too much attention to their mobile devices (Specht, Ternier, & Greller, 2011).

Classroom is a preferable environment among AR studies (Ajit, Lucas, & Kanyan, 2021). AR serious games played in the classroom could increase the face-to-face collaboration among students (e.g., Freitas and Campos, 2008; Dunleavy, Dede, & Mitchell, 2009), and get help and feedback from their teachers when they encountered problems or had questions immediately (e.g., Cascales *et al.*, 2012). However, previous research also identified that informal settings, including activities outside classroom (e.g., home, field-trip), might produce better learning outcomes than formal settings (e.g., classroom, laboratory) (Garzón and Acevedo, 2019). Therefore, AR technology could be integrated in everyday activities more instead of just using AR serious games within the classrooms (Ajit, Lucas, & Kanyan, 2021). We also found AR games with no limit for the environment, or can be played both in the classroom, at home, and at a museum (e.g., Hsiao et al., 2016), and AR serious games designed specifically for playing at home with the help of parents (e.g., Lee and Lee, 2008).

2.3.2 Effects on Learning Achievement and Motivation

We have classified the effects of AR serious games into two main categories, which were learning achievement and motivation.

Regarding the learning achievement, previous studies reported that AR serious games led to effective outcomes in achieving learning gains (e.g., Chen and Tsai, 2012; Hwang *et al.*, 2016; Ibáñez *et al.*, 2014). The positive effects also included the enhancement of learning efficiency and cognitive skills like problem-solving skills, critical thinking skills, multi-tasking skills, and so on (e.g., Di Serio, Ibáñez, & Kloos, 2013; Lu and Liu, 2015; Schrier, 2006). Di Serio, Ibáñez, & Kloos (2013) and Cheng (2017) also reported that the use of AR serious games could reduce the cognitive load of students, while another study showed that students felt frequently overloaded and confused due to the large amount of materials and tasks during the game play (Dunleavy, Dede, & Mitchell, 2009).

The motivation aspects involved different focuses, such as engagement, satisfaction, fun, enjoyment, interest, attention, confidence, and positive attitudes of students. Previous studies frequently reported that students described the learning experience with AR games as joyful and playful (Di Serio, Ibáñez, & Kloos, 2013) as they had fun playing AR games to learn school knowledge (Lu and Liu, 2015). We found that students mentioned AR serious games as fun, interesting, or enjoyable, in studies about AR gaming in sustainable design education (Ayer, Messner, & Anumba, 2016), and mathematical education games based on AR (Lee and Lee, 2008). Previous studies also reported that AR serious games engaged them more than traditional learning methods (e.g., Bressler and Bodzin, 2013; Di Ibáñez, & Kloos, 2013). In addition to these two effects, AR serious games were also evaluated to "*enhance satisfaction*" (Cascales *et al.*, 2012), "*enhance the willingness to learn*" (Lin *et al.*, 2011), "*enhance attention*" (Lu and Liu, 2015), "*enhance confidence*" (Lin *et al.*, 2011), and "*enhance positive learning attitude*" (Hsiao, Chen, & Huang, 2012).

Different measures were used to evaluate the effects caused by AR serious games. We found that a frequently used measure of learning achievement was a pre-test and post-test of knowledge that examines the improvement of knowledge content learning of students before and after the use of AR serious games (e.g., Lu and Liu, 2015). Some studies only used a post-test in their experiments (e.g., Cascales et al., 2012). Regarding the motivational aspect, some previous studies applied observation as the main evaluation method during students' learning and playing process (e.g., Chen and Tsai, 2012). The questionnaires were popular in measuring motivation in previous work (e.g., Schrier, 2006). Some studies introduced and explained the questionnaire questions in their studies and Keller's ARCS Motivation Model (Keller, 1987) was frequently adopted as the motivation questionnaire (e.g., Di, Ibáñez, & Kloos, 2013). In contrast, some studies did not explain how they created and evaluated their questionnaire questions to measure the motivation accurately. Interviews as a way to collect qualitative data were also widely applied. Pre-survey and post-survey were used to investigate the changes of attitudes before and after the use of AR games. Table 2.2 shows the examples of research with different effects and different measurement methods.

Table 2.2 The effects and measurement methods of AR serious games.

Achievement		**Example of Research**
Learning Achievement	Enhance learning performance	Hwang *et al.*, 2016
	Acquire target knowledge	Lu and Liu, 2015
	Learn effectively	Di Serio, Ibáñez, & Kloos, 2013
	Enhance cognitive skills	Schrier, 2006
	Reduce cognitive load	Cheng, 2017
Motivation	Fun, interesting, enjoyable	Pombo and Marques, 2020
	Enhance engagement	Bressler and Bodzin, 2013
	Enhance satisfaction	Cascales *et al.*, 2012
	Willingness to learn	Lin *et al.*, 2011
	Positive attitude	Chen, Chou, & Huang, 2016
	Enhance attention	Lu and Liu, 2015
	Enhance confidence	Lin *et al.*, 2011
Measurement Method		**Example of Research**
Learning Achievement	Pre-test and post-test	Lu and Liu, 2015
	Post-test only	Cascales *et al.*, 2012
Motivation	Observation	Bressler and Bodzin, 2013
	Questionnaire	Pombo and Marques, 2020
	Interview	Dunleavy, Dede, & Mitchell, 2009
	Pre-survey and post-survey	Schrier, 2006

2.3.3 Effects on Social Interactions

Social interactions have emerged to be the main advantages of AR in education (Bacca Acosta *et al.*, 2014), which could enhance the interactions between learners, teachers, and the environment (Ajit, Lucas, & Kanyan, 2021). Based on previous studies, we found three main types of social interactions, which were interactions among students, between teachers and students, and between students and parents. In some AR serious games, students were required to work collaboratively in groups to solve a particular task, while the competition among groups was also promoted. Table 2.3 shows the example of research with social interactions. Unlike the rich social interactions among students, the most common social interaction between students and teachers, and students and parents, was guidance and help. Frequently, little attention was paid to the study of how these social interactions affected learning achievement or motivation in turn. The attitude from classmates, the feedback from teachers, and the help from parents may all impact children's learning experience. In Chapter 5, we identified more latest studies concentrated on the collaboration and competition among students (e.g., Costa *et al.*, 2018; Laine, 2018).

Table 2.3 Social interactions in AR serious games.

Type		Example of Research
Student-student	Collaboration	Boletsis and McCallum, 2013
	Competition	Pombo *et al.*, 2017
	Share	Di Serio, Ibáñez, & Kloos, 2013
	Reflection	Squire and Jan, 2007
	Enhance confidence	Lin *et al.*, 2011
Student-teacher	Guidance	Wei, Guo, & Weng, 2018
Student-parents	Guidance	Lee and Lee, 2008

2.3.4 AR Features and Game Mechanics

AR serious games include, among others, AR features and game mechanics. Different features or mechanics may have different outcomes regarding learning achievement and motivation mentioned above. Therefore, we sought to identify the frequently used AR features and game mechanics in AR serious games.

We found that the game mechanism of time limitation (e.g., Bressler and Bodzin, 2013), quiz-based games (e.g., Di Serio, Ibáñez, & Kloos, 2013), inquiry-based games (e.g., Efstathiou, Kyza, & Georgiou, 2018), and puzzles (Eleftheria *et al.*, 2013) were preferred and commonly used in previous studies. Game story (e.g., Chen and Tsai, 2012) was also frequently included in AR serious game design, which allows students to start the game with a story or background information (Chen and Tsai, 2012). Some of them might play a role during the game (e.g., Schrier, 2006). Another frequently used game element was collection (e.g., Boletsis and McCallum, 2013). Players tried to look for different information and collect them to achieve the goals. The term goals was widely used in previous studies, including getting certain points, rewards, or finish a task (e.g., Lu and Liu, 2015). Secret missions or hidden content were also included in some games (e.g., Hwang *et al.*, 2016), of which the process of looking for the hidden mission might stimulate the interest of the students. The factor of feedback (e.g., Freitas and Campos, 2008; Oppermann, Blum, & Shekow, 2016) and the form of board games (e.g., Lee and Lee, 2008; Yu and Denham, 2019) were also found as the game design mechanics in previous studies. Laine (2018) categorized the game mechanics used in previous AR serious games and found that puzzle games and treasure hunting games are the dominating game mechanics. Other game mechanics included action games, simulation games, board games, and story-driven adventure (Laine, 2018). Table 2.4 shows the examples of research with different game mechanics.

Table 2.4 Game mechanics and AR features in AR serious games.

Game mechanics	Example of Research
Goals	Lu and Liu, 2015
Quiz-based	Di Serio, Ibáñez, & Kloos, 2013
Time limitation	Bressler and Bodzin, 2013
Game story	Chen and Tsai, 2012
Inquiry-based	Efstathiou, Kyza, & Georgiou, 2018
Collection games	Pombo and Marques, 2020
Puzzles solving	Eleftheria *et al.*, 2013
Role play	Schrier, 2006
Secret missions	Hwang *et al.*, 2016
Treasure hunting	Alakärppä et al., 2017
Action games	Revelle et al., 2014
Simulation games	Lan, 2013
Feedback	Oppermann, Blum, & Shekow, 2016
Board games	Yu and Denham, 2019
AR features	**Example of Research**
Location-based	Atwood-Blaine and Hufman, 2017
Image-based	Chen and Tsai, 2012; Hung et al., 2017
Extra material	Boletsis and McCallum, 2013
3D model	Freitas and Campos, 2008
Face-to-face	Kamarainen *et al.*, 2013
Physical model	Hsiao, Chen, & Huang, 2012
AR presentation agent	Eleftheria *et al.*, 2013
Gesture-based input	Munsinger, White, & Quarles, 2019

According to Boletsis and McCallum (2013), the use of AR features could reveal "hidden" objects to explore, which makes students feel special and excited, seeing "invisible" stuff. Previous AR applications included location-based AR (e.g., Lu and Liu, 2015) and image-based AR (e.g., Chen and Tsai, 2012). Some applications included extra instructional materials, such as text, video, and audio, since that the visualization of knowledge content can promote the fun experience of AR serious games for students (e.g., Boletsis and McCallum, 2013). The 3D models also appeared frequently in AR serious games (e.g., Freitas and Campos, 2008). Apart from that, some AR serious games used physical objects, allowing students to interact in the game using physical models (e.g., Hsiao, Chen, & Huang, 2012). In addition, as communication in the real world is the main advantage of AR serious games (as opposed to regular video games), previous studies often encouraged face-to-face interactions in their games (e.g., Kamarainen *et al.*, 2013). AR presentation avatar (e.g., Eleftheria *et al.*, 2013) and gesture-based input (e.g., Enyedy *et al.*, 2012; Munsinger, White, & Quarles, 2019) were also mentioned in previous studies. Most of the previous studies involved more than one AR feature. See Table 2.5 for examples of AR features appearing in previous studies.

2.3.5 Suggestions for Designing AR Serious Games based on Literature

Based on previous studies, we can discern recommendations for the design of AR serious games that potentially lead to positive effects on students. Generally speaking, during the design process, five aspects should be considered: involving learners in the design process; setting clear serious objectives; identifying effects of AR features; studying the game mechanics; and encouraging and investigating AR social interactions.

Involving learners in the design process.

From previous studies, we found that AR serious games might have different types of effects on different students. However, although some studies have designed different content for different target groups, overall, there is a lack of focus on designing the game concepts together with students in previous AR serious games. When designing an AR serious game, the designers should try to involve the target learner groups in the design process, asking their preferences for the initial game concepts and collecting feedback for future iterations. Besides, one advantage of AR serious games compared to traditional learning is that it can present different content to different students under the same physical environment (Chen and Tsai, 2012). One could consider to provide different content to different students based on their interests or needs.

Setting clear serious objectives.

We found a variety of effects of AR serious games, from learning achievement to motivational aspects. It is hard to achieve all of these effects in one game. Therefore, it is important to have specific and clear serious objectives. Some games focused on the improvement of students' knowledge performance (e.g., Eleftheria *et al.*, 2013), some might just want to make students feel more positive about studying (e.g., Kamarainen *et al.*, 2013), while some aimed at the development of cognitive skills, such as investigation and inquiry skills (e.g., Wojciechowski and Cellary, 2013). Clear educational objectives are essential for the design of an effective AR serious game. Only when the educational objectives are clear, the proper game mechanics and AR features can be selected, and effective AR serious games can be designed.

Identifying the effects of AR features.

AR technology, which makes AR serious games different from other learning games, encompasses various features, including the use of an AR avatar, physical objects, extra instructional materials (e.g., video, audio, text, etc.), and so on. We found that most of the previous AR serious game designs involved more than one AR feature. However, previous studies only evaluated the overall experience of students using the AR serious games, without investigating the specific effects of each feature like the studies have done in traditional serious games. The specific effects of different kinds of AR features were not well studied. Identifying different outcomes and effects of each feature specifically could help design motivating AR serious games more effectively, which should be brought to the forefront of attention.

Studying the game mechanics.

Like AR features, we also found more than ten types of game mechanics in previous AR serious games. Designers should study the game mechanics and understand how to use different game mechanics to improve learning achievement and motivation. We found some researchers already took game mechanics into consideration when they designed the AR serious games. For example, "*clear goals*", "*equilibrium between challenge and personal skill*", "*merging of action and awareness*", "*focused attention*", "*control*", "*loss of self-consciousness*", "*time distortion*", as well as "*self-rewarding*" were mentioned in a study (Eleftheria *et al.*, 2013). Laine (2018) proposed guidelines related to the game mechanics, including "combining game genres", "getting a skilled designer to create AR content and the game appearance in general", and "using a gameplay model to design many different gameplay components". In another study by Squire and Jan (2007), game design mechanics such as "*asking students to inhabit roles*", "*activity are organized around challenges*", etc., were also addressed in an AR game on science education. On the other hand, many studies ignored the game mechanics or did not mention them explicitly in their research.

Encouraging and investigating AR social interactions.

AR offers opportunities to increase communication and interactions (Kamarainen *et al.*, 2013; Zarraonandia *et al.*, 2013), which should be encouraged in AR serious games. However, few previous studies have paid attention to utilize the AR-specific affordance to encourage social interactions in both the virtual and real world. On the contrary, we even found one study included a chat room in the game to encourage social behavior (Bressler and Bodzin, 2013), which allowed students to talk online with the potential to prevent students from talking to each other in the real world. Some other studies allowed users to share information, solve puzzles together, or exchange game items face-to-face in the real world. Besides, we noticed that previous studies focused mostly on the subjective feelings of students on the AR experience without understanding how they perceived the interactions with each other or with the learning materials in the AR settings particularly. Designers should have a deeper understanding of how to amplify the advantages of social interactions in AR serious games by investigating questions like which types of social interactions should we integrate in AR serious games and how do students perceive their social interactions with each other?

2.4 Self-Determination Theory and Game Design Mechanics

2.4.1 Self-Determination Theory

In our study, we apply SDT as the fundamental theory to understand motivational aspects of different mechanics in AR serious games. SDT is a psychological theory of human motivation, growth, and well-being (Deci and Ryan, 2000; Deci and Ryan, 2002; Ryan and Deci, 2017). SDT suggests that intrinsic motivation plays the core role underlying play (Frederick and Ryan, 1993, 1995), which is an "*innate human propensity for activities perceived as interesting and enjoyable*" (Tyack and Mekler, 2020, pp.2). Most game players typically play computer games because they are intrinsically motivating or "fun" (Malone and Lepper, 1987; Bartle, 2004). According to Ryan and Deci (2000a, 2000b), there are three basic psychological needs for people: competence, autonomy, and relatedness. Satisfaction of these needs improves intrinsic motivation (Tyack and Mekler, 2020), where an individual can become motivated to act (Deci *et al.*, 1994).

The reason we chose SDT as a theoretical framework is multifold. First of all, SDT is one of the most established theoretical frameworks for intrinsic motivation research in digital games and education with empirical support (Deterding, 2015; Dean, Dunn, & Tomcheck, 2015). In the context of education, the psychological needs for competence, autonomy, and relatedness have been shown to be positively associated with learning motivation (Rigby *et al.*, 1992). Secondly, SDT brings forth in more ways to assess motivation than being either “high” or “low” (e.g., perceived competence, relatedness, autonomy), presenting us with “better insights of the possible effects of different features on users’ motivation” as well as “clear tools to design with” (Deen, 2015, pp.135). In addition, we should address the issue of how different aspects of game design mechanics actually affect different motivational outcomes. SDT and psychological needs are suitable concepts for investigating the effects of different aspects of game design mechanics (Sailer *et al.*, 2017). Figure 2.1 shows the elements within SDT.

Figure 2.1 Self-Determination Theory (Deci and Ryan, 1985; Deci and Ryan, 2000; Ryan and Deci, 2000b).

- Competence refers to the individual’s sense of self-efficacy, which describes an individual’s belief in being able to successfully overcome challenges (Bandura, 1997) and success while interacting with the environment (Rigby and Ryan, 2011; Vansteenkiste and Ryan, 2013). It suggests the perceived extent of one’s own interaction as the cause of desired consequence in the environment and increases when the player is provided with positive feedback (Deci and Ryan, 2002; Ryan and Deci, 2000b; Ryan, Rigby, and Przybylski, 2006; Santos et al., 2015).

- Relatedness refers to feelings of social connectedness with other people (Deci and Ryan, 2002; Ryan and Deci, 2000b; Sailer et al., 2017). The need for relatedness can be satisfied by interacting with the "significant others" (individuals with whom people have a meaningful connection with (Ryan and Deci, 2000b)) (Dean, Dunn, & Tomcheck, 2015). Relatedness represents the basic desire of people interacting with the social environment (Baumeister and Leary, 2017; Deci and Ryan, 1985, 2000; Deci and Vansteenkiste, 2003).
- Autonomy concerns a sense of volition or willingness when doing a task (Ryan and Deci, 2006; Ryan, Rigby, & Przybylski, 2006), which offers an opportunity for people to generate their own path (Dean, Dunn, & Tomcheck, 2015). According to SDT, people who are autonomous-supportive feel that they are responsible for their own progress (Dean, Dunn, & Tomcheck, 2015). According to Sailer et al. (2017), autonomy refers to the experience of decision freedom and task meaningfulness. Decision freedom implies being able to choose between several courses of actions, and task meaningfulness means that the course of action conforms with one's own goals (Sailer et al., 2017).

Motivation can be significantly increased by addressing these three psychological needs (Sailer *et al.*, 2017; Vansteenkiste, Niemiec, & Soenens, 2010). In the educational domain, the satisfaction of competence, autonomy and relatedness can actively transform the external regulations into inner values, leading to enhanced creativity and improved learning outcomes (Ryan, 1995; Ryan and Deci, 2000a). This type of integration refers to internalization in which the individual "*identifies with the value of an activity and accepts full responsibility for doing it*" (Deci et al., 1994, pp.121), making people feel that they are in charge of their action and progression (Deci and Ryan, 1994).

2.4.2 Game Design Mechanics and PLEX

As the three intrinsic psychological needs can be applied as motivational resources by modifying the learning environment, in the context of serious games, we matched game design mechanics to these psychological needs specifically to investigate the effects on children’s motivation.

Game design mechanics are the basic building blocks of gamification applications (Deterding *et al.*, 2011; Werbach and Hunter, 2012). Reeves and Read (2009) have proposed mechanics to develop a successful game, including the representation of oneself through avatars, narrative context, feedback, competition, and teammates. In addition, Werbach and Hunter (2012) have identified 15 important components in game design, including avatars, badges, leaderboards, points, teammates, etc.

In previous game research, scholars have matched the need for competence to game mechanics of points/scores for providing feedback that can be directly related to the actions of the player, performance graphs for visually indicating players’ progress, badges or leaderboards for assessing a series of player actions and providing cumulative feedback in turn (Hense and Mandl, 2014; Sailer *et al.*, 2014). According to Sailer *et al.* (2017), feedback is one of the essential game design mechanics that can evoke feelings of competence.

The need for relatedness has been found to be affected by teammates, including the teammates in the real world and non-player characters in the digital game (Groh, 2012; Rigby and Ryan, 2011). Besides, a shared goal can also foster the experience of social belongings, which should be conveyed within a meaningful story (Sailer *et al.*, 2014).

Regarding the need for autonomy, prior studies have matched two main aspects, including the experience of decision freedom and the experience of task meaningfulness (Sailer *et al.*, 2017). The freedom of decision should offer the players freedom of choices (Annetta, 2010; Peng *et al.*, 2012). In task meaningfulness, the game story plays an important role in helping players experience their own actions as meaningful and volitionally engaging, regardless of whether the choice is provided or not (Rigby and Ryan, 2011).

However, although studies have addressed matching the game mechanics to the psychological needs, empirical research regarding the effects of specific game design mechanics is still lacking (Mekler *et al.*, 2017; Seaborn and Fels, 2015). Besides, Mekler *et al.* (2017) have also claimed that they could not observe substantial effects of the game design mechanics of points, leaderboards, and levels on the need satisfaction despite the effects on the performance. Previous studies have addressed the research gap of a lack between the experimental design and the effects of game design mechanics (e.g., Bedwell *et al.*, 2012; Hamari, Koivisto, & Sarsa, 2014; Sailer *et al.*, 2017; Seaborn and Fels, 2015). The research which focuses on AR serious games is also scarce, yet it is essential to understand how specific game design mechanics in AR settings affect psychological need satisfaction to provide a more engaging and motivating learning experience for children. To this end, in our study, we matched the game design elements in PLEX (Arrasvuori, Boberg, & Korhonen, 2010; Korhonen, Montola, & Arrasvuori, 2009) to SDT.

The PLEX framework is a categorization of playful experiences based on previous theoretical work on pleasurable experience, elements of play, and reasons why people play (Korhonen, Montola, & Arrasvuori, 2009). The framework aims at helping designers understand the underlying fundamental elements of pleasure or play (Korhonen, Montola, & Arrasvuori, 2009). The PLEX framework identified 22 Playful Experience categories (shown in Table 2.5) (Arrasvuori *et al.*, 2011; Korhonen, Montola, & Arrasvuori, 2009; Lucero and Arrasvuori, 2013).

In Chapter 1, we gave a preview of the categories we included in our research. Here we would explain the selection process further. We excluded the categories that might not be suitable for AR educational games for children. For example, AR enables interactions with the real-world, thus it is not ideal to forget one's surroundings (captivation). Different from the social connectedness perceived in the fellowship, sympathy focuses more on emotional feelings, including happiness and sadness. Control is perceived as dominating -- players "playing the god" and becoming powerful (Korhonen, Montola, & Arrasvuori, 2009), which is also not highly related to the AR educational game. Expression addresses the creation in a fashion and creative way, which is not in line with the outcomes of our game. All games that are not abstract could have a simulation element provided (Lucero and Arrasvuori, 2013), which we also excluded. We included exploration instead of discovery because exploration is the action, which could lead to discovery as a consequence (Lucero and Arrasvuori, 2010). The rest of the categories are not suitable for children: cruelty, eroticism, humor, nurture, relaxation, sensation, submission, subversion, suffering, and thrill.

In the end, we elicited the playfulness categories to challenge, competition, completion, exploration, fantasy, and fellowship. Here we explain each of these categories further based on the category proposed by Korhonen, Montola, & Arrasvuori (2009):

- Challenge: experience of having to develop and exercise skills in a challenging situation;
- Competition: experience of victory-oriented competition against oneself, opponent or system;
- Completion: experience of completion, finishing and closure, in relation to an earlier task or tension;
- Exploration: experience of exploring or investigating a world, affordance, puzzle or situation;
- Fantasy: experience of make-believe involving fantastical narratives, worlds or characters;
- Fellowship: experience of friendship, fellowship, communality or intimacy.

Based on the meaning and explanation of the three psychological need, we mapped each playful category in the PLEX framework to SDT: the challenge and completion were mapped to competence; competition and fellowship to relatedness; exploration and fantasy to autonomy.

Table 2.5 The PLEX framework consisting of 22 categories (Arrasvuori *et al.*, 2011; Korhonen, Montola, & Arrasvuori, 2009; Lucero and Arrasvuori, 2013).

Experience	Description
Captivation	Forgetting one's surroundings
Challenge*	Testing abilities and exercise skills in a demanding task
Competition*	Contest with oneself or an opponent
Completion*	Finishing a major task, closure
Control	Dominating, commanding, regulating
Cruelty	Causing mental or physical pain
Discovery	Finding something new or unknown
Eroticism	A sexually arousing experience
Exploration*	Investigating an object or situation
Expression	Manifesting oneself creatively
Fantasy*	An imagined experience
Fellowship*	Friendship, communality or intimacy
Humor	Fun, joy, amusement, jokes, gags
Nurture	Taking care of oneself or others
Relaxation	Relief from bodily or mental work
Sensation	Excitement by stimulating senses
Simulation	An imitation of everyday life
Submission	Being part of a larger structure
Subversion	Breaking social rules and norms
Suffering	Experience of loss, frustration, anger
Sympathy	Sharing emotional feelings
Thrill	Excitement derived from risk, danger

** The categories we chose*

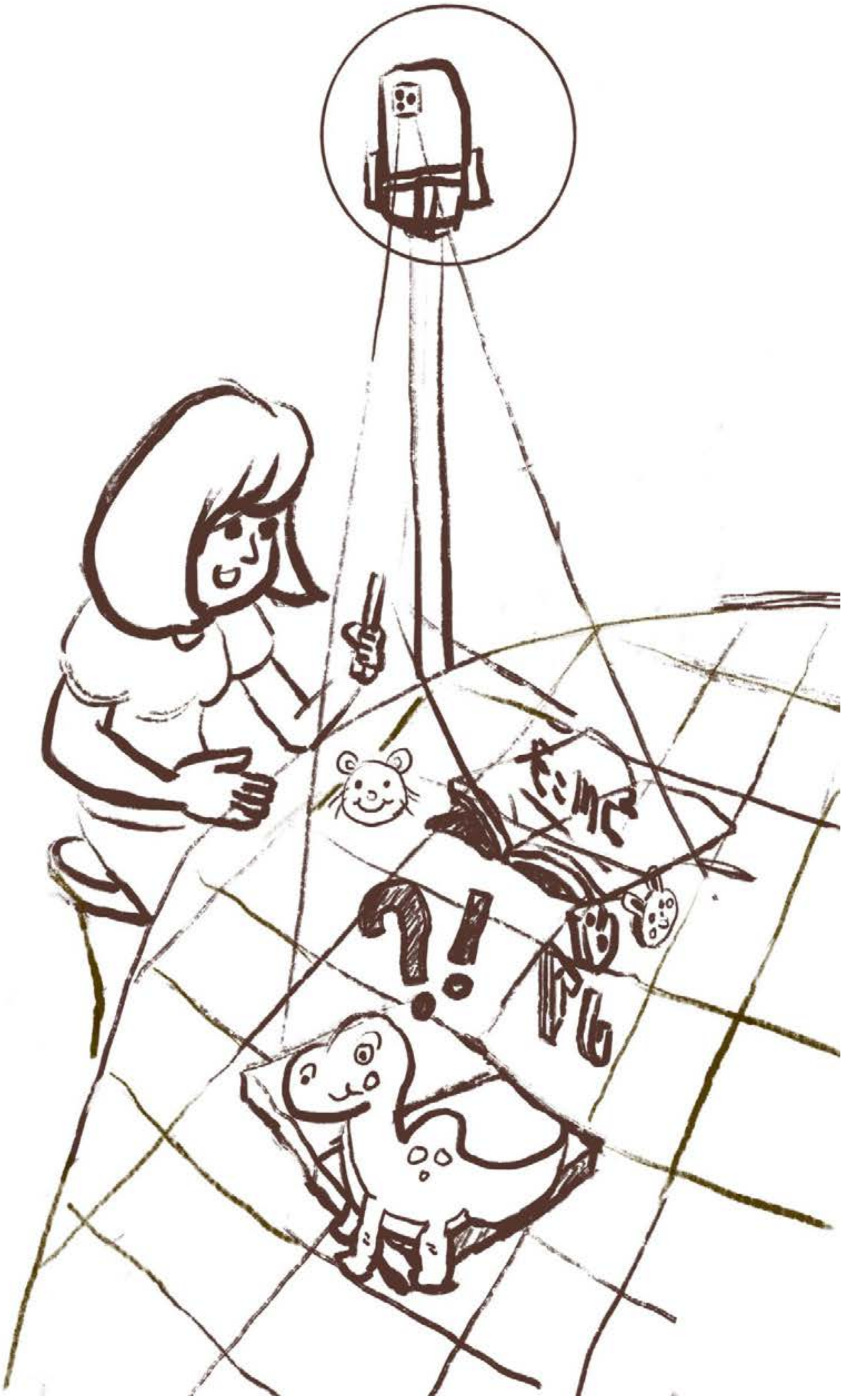
2.5 Summary

One of the aims of HCI games research is to understand how to make engaging player-computer interaction (Malone, 1981), which in turn may be applied to design activities that motivate people to engage with purposes beyond entertainment, such as serious games (Tyack and Mekler, 2020). In this chapter, based on previous literature, we described the potential of AR serious games to enhance children's learning motivation. We investigated the existing design guidelines for AR serious games and found out the gaps in systematically and practically tested design guidelines. We learned the state of the art of AR serious games and understood the current situation to better chart our future design space. In the end, we introduced the theoretical frameworks supporting this research, which were SDT and PLEX. In the next chapter, we start to look into the concrete game features and game concepts to build upon these previous works.

CHAPTER

THREE

CONCEPT EXPLORATION



Chapter 3: Concept Exploration[2]

In Chapter 2, we reviewed previous work on the motivational effects in AR serious games, design guidelines, and the state of the art of AR serious games, as well as SDT and PLEX. We suggested setting clear objectives for the AR serious games and involve target groups in the early design process. Therefore, in this research, we first used participatory design as a design method to come up with the basic concepts of an AR game, finding out which kinds of game concepts and content would be preferred by children. Then, we conducted a cross-cultural study with 38 children from two different cultures, China and the Netherlands, to collect feedback for future iterations. In this chapter, we first present the participatory design sessions, and then present the AR serious game See Me Roar designed and developed based on the findings from the participatory design sessions, following with the results of the experiments on what the differences are between paper exercises and AR game exercises, and what the cultural differences are in children's attitudes towards the two types of exercises.

3.1 Elementary School Mathematics as the Learning Topic

In this research, we chose mathematics as the learning topic for several reasons. Firstly, mathematics learning has been a primary concern in the educational system around the world, as children frequently experience mathematics as a difficult subject during their elementary school years (van Steenbrugge, Valcke, & Desoete, 2010), which demands more effort than many other school subjects (Eccles, Adler, & Meece, 1984; Grouws and Lembke, 1996; Stodolsky, Salk, & Glaessner, 1991). Consequently, learning motivation and interests are suggested playing an important role in children's mathematics performance at school (Eccles

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[2] **Based on:**

Li J., van der Spek E., Hu J., Feijs L. (2018). See Me Roar: On the Over-Positive, Cross-Cultural Response on an AR Game for maths Learning. In *Joint International Conference on Serious Games* (pp. 54-65). Springer, Cham.

et al., 1983; Freedman-Doan *et al.*, 2000; Gottfried, 1990). According to previous studies, the level of learning motivation could predict children's subsequent mathematics performance (Gottfried, 1990; Gottfried, Fleming, & Gottfried, 1994) as well as their decisions to continue taking mathematics courses (Meece, Wigfield, & Eccles, 1990). On the contrary, low feelings of competence and engagement for mathematics may predict poorer mathematics performance (Aunola, Leskinen, & Nurmi, 2006; Frenzel, Pekrun, & Goetz, 2007). Secondly, children's performance in mathematics may predict their subsequent task motivation at the very early stage of their school years (Aunola, Leskinen, & Nurmi, 2006). During the first and second elementary school years, a high level of mathematics-related motivation would further contribute positively to children's learning performance (Aunola, Leskinen, & Nurmi, 2006). Early experiences of mathematics, such as one's performance and feedback received, would also contribute to the development of their mathematics-related motivation (Freedman-Doan *et al.*, 2000; Gottfried, 1990). Thirdly, according to our literature review in Chapter 2, science and biology were highly focused subjects in previous AR studies. The studies of physics, history, and art and design were second preferred subjects. The connection of these subjects with AR could be more direct with more specific content to be integrated with (e.g., 3D models of planets), while we did not want to pick low-hanging fruit by choosing an easier topic, especially since we planned to produce generalized knowledge about AR features and game mechanics in designing motivating AR serious games for children. Therefore, we chose mathematics as a carrier for the research of AR serious games.

3.2 Approach: Participatory Design

We applied the participatory design method to involve the target users from an early process and thereby to get useful information to feed into the game design and increase the possibility that the game concepts would be accepted and liked by the target age group (Kuhn and Muller, 1993). Two elementary school children aged seven were invited. Overall, we have conducted four participatory design sessions, each took around 45 minutes, where children could express their thoughts and share their ideas about the game design. The participatory design sessions took place in a classroom in a Dutch school building in Eindhoven (see Figure 3.1). We followed the basic approaches in participatory design, including *stage 1: initial exploration of work*; *stage 2: discovery processes*; and *stage 3: prototyping* (Spinuzzi, 2005). The stages can be iterated for several times and could provide an iterative co-exploration by the designers and the end users (Spinuzzi, 2005).

Figure 3.1 Participatory design session with two elementary school children.

In the first stage of the initial exploration of work, designers should meet the target users and get familiar with the technologies they used, their routines, and other aspects of their work (Spinuzzi, 2005). Thus, in our first participatory design session, we tried to familiarize ourselves with the children and understand them better. We introduced ourselves and asked children questions about the textbook they were using, their feelings about mathematics, and their behaviors in the game usage. After the first session, we had the following findings:

- These two children liked playing digital games a lot. The games they liked to play were *Clash Royale*, *SimCity*, and *Minecraft*:
    - Clash Royale[3] -- "I can play with my friends"; SimCity[4] -- "I can build my own city the way I like, very tall buildings"; Minecraft[5] -- "I can do a lot of things in Minecraft".
- They would spend a lot of time playing games at home on school days, while more on the weekends and holidays:
    - On school days -- "*I would spend 1.5 hours to 3 hours with my iPad*"; On the weekend -- "*I don't know how long, but I can play longer*".
- They liked learning mathematics. The mathematics textbook they were using was a Dutch mathematics textbook for group 5[6] (with consent by the book publisher Rekenrijk). See Figure 3.2.

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[3] **Clash Royale:** a real-time strategy video game developed and published by Supercell. https://clashroyale.com/

[4] **SimCity:** an open-ended city-building video game series originally designed by Will Wright. https://www.ea.com/games/simcity

[5] **Minecraft:** a sandbox video game developed by Mojang. https://www.minecraft.net/en-us

[6] Dutch elementary school (lagere school) has eight grades, known as groepen, ranging from Groep 1 (4-year-olds) to Groep 8 (12-year-olds). It is not compulsory to attend primary school until Groep 2, at age five, but most children begin in Groep 1 already at the age of four. Children in Groep 5 are around 8 years old. Source: https://www.iamexpat.nl/education/primary-secondary-education/dutch-school-system

Figure 3.2 Textbook used in the current AR prototype (Rekenrijk group).

The second participatory design session took place in the same room one week later. We presented the background to the two children that we were going to design a digital game for mathematics learning. We first encouraged them to brainstorm with us and draw the elements they would like to see in the game. Figure 3.3 shows their drawings and thoughts produced in the second participatory design session, which have provided us the source of the original game concepts:

- Children liked the idea of animals:
    - One child drew an elephant. The other one drew a little farm with an animal inside it.
- Children would connect their experiences in real life and with the games they have played before to the new game:
    - The first child also drew some water and food around the elephant. The game idea resembled Minecraft. The other one drew a small farm and tall buildings, expressing that he would

like to trade by planting vegetables and raising animals in the farm to upgrade his buildings. Then he started to describe the rules from the game SimCity.

Figure 3.3 Drawings by the children from the participatory design session.

The second participatory design session inspired us with the concept of animals in the game. After that, we wanted to collect more detailed information about the types of the animals, as well as how they would be connected to a mathematics exercise. Hence, in the third session, we kept asking for their preferences in the types of the animals, the characters with which they wanted themselves to be represented in the game, the ways they found interesting to do a mathematics exercise in the game, and the rewards they would like to receive. We found that children still preferred the ideas of animals and feeding the animals, and even related it with the mathematics exercises:

- They would like to get the animals they have seen in the real world, such as a dog, tiger, lion, elephant, etc.;
- They would like to use the characters from the game Clash Royale to represent themselves;
- They would like the mathematics exercises to be related with the animals:
    - For example, one exercise could be "*the animal needs to eat five apples and eight bananas, how many items should we give?*"
- They would like to receive food as rewards that could be used to feed the animals later in the game.

Then we proceeded to the prototyping stage with the information collected from children. According to Huang (2018), when developing AR applications, one might encounter much more difficulties than traditional games. It takes both more time and costs of developing AR applications than other mobile applications. Thus, a low-fidelity prototype, which is quick to make, inexpensive, and easy to adjust and share (Buxton, 2010), could be a valuable tool to avoid wasting resources of development and collect feedback as early as possible in the early developing stage (Huang, 2018). Therefore, between the third and fourth sessions, we started experimenting with AR and building up some AR features based on the findings from the second and the third sessions. We created a quick AR prototype with a few selected animals above a textbook:

- The animals are common animals that children are familiar with, such as the elephant, ox, goat, tiger, and lion;
- The animals appear on top of the mathematics textbook these children currently use in the school;
- The animals will talk to the player, and there is a mathematics exercise in their conversation;
- There are 2D images of fruits and vegetables showing in the game. The current game has no further interaction.

In the fourth participatory design session, we showed the initial game prototype to the two children as described above based on their previous ideas. See Figure 3.4 for the game prototype, See Me Roar. Children were excited to see the animals walking around on their textbooks. They used the word “cool” several times. Both the children said they liked the current animals and would like to see more animals. When asked about what they wanted to do with the animals, the children said that they wanted to become friends with the animals, and then they could see the animals do some tricks, like an elephant playing with a ball. When they received the mathematics exercise from the animal, they thought that the exercise was quite easy for them to answer. It would be more efficacious if the exercises have different difficulty levels, which was aligned with the perspective of flow theory (Shernoff *et al.*, 2014).

We also showed the game to an elementary school teacher. The elementary school teacher said that using AR games could be a good way to make mathematics more fun and easier for children to learn. The teacher commented on See Me Roar as “looks cool”, “good idea”, and “helpful”. The teacher also mentioned that it might be a good idea to involve other subjects, such as history and geography, in the AR game.

Figure 3.4 Initial concepts based on the first three participatory design sessions.

3.3 Game Concepts of See Me Roar

Based on the results from the participatory design sessions with the two 7-year-old children from a Dutch elementary school, we designed and developed the first version of the AR game, See Me Roar. The current version is the base game with basic functions, aiming to provide children with motivating learning experience when doing their mathematics exercises. The game concept of See Me Roar is described below:

In the beginning of the game, children are told that there are animals in their textbook waiting for their help to solve maths problems. Then, children start to scan the textbook and find animals. When an animal shows up (Figure 3.5 top-left), children can interact with the animal by touch-input, leading to a series of different actions, such as lying down, jumping, or flying. Children can control animals to move around (the round button in Figure 3.5). A relationship bar with the animal shows up on the right corner of the screen, starting from 0 points. Children have to find ways to build a relationship with the animal. They can open their bag that contains food and choose some of them to feed the animals (Figure 3.5 top-middle). For each food item there is a description of animal preferences (Figure 3.5 top-right). Once the relationship bar achieves 100 points, an exercise interface will appear, and children can write their answer to the displayed exercise (Figure 3.5 bottom-left) (the exercises match their learning progress in their textbooks). Upon completion, children will get immediate feedback showing right or wrong answered questions accompanied by either a gift as a reward from the animal (Figure 3.5 bottom-middle), or an encouraging message for them to keep going (Figure 3.5 bottom-right). Different animals carry exercises with different difficulty levels based on the rarity of encountering them.

Before we could fill in the AR game with more features based on SDT, the psychological theory we applied in this study (see Chapter 2), we first conducted an experiment to see if the current game concepts would be accepted by children. Previous studies have already shown that the potential of applying serious games could lead to increased enjoyment, desire for future play, recommendation to others, and more positive ratings of the game (Peng *et al.*, 2012; Przybylski, Rigby, & Ryan, 2010; Ryan, Rigby, & Przybylski, 2006; Tamborini *et al.*, 2010). Therefore, we proposed our first hypothesis:

H1. The AR game will improve children's motivational factors over a paper version in terms of (a) enjoyment, (b) desire to do the exercise in free time, (c) recommendation to others, (d) perceived fun of doing math, (e) likability of the experience.

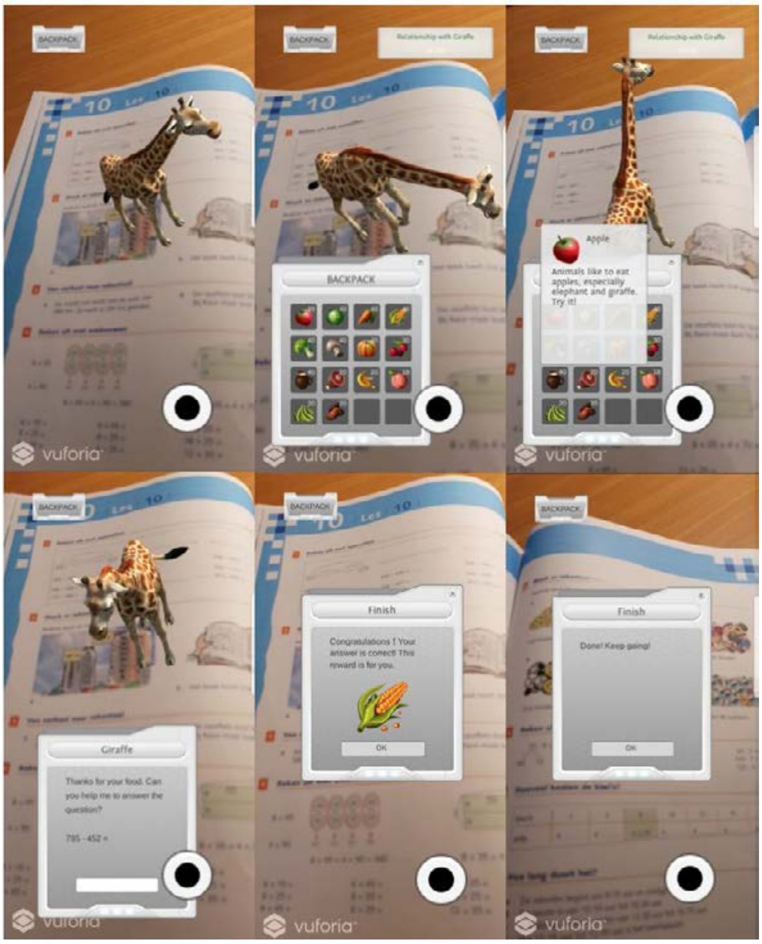

Figure 3.5 Game concepts of See Me Roar (up-left: animal appears; up-middle: interacting with animal; up-right: description of food; down-left: exercise interface; down-middle: reward; down-right: encouraging message).

3.4 Cultural Differences

It was not our original intention of the main research direction to study cultural differences. However, we saw practical opportunities to test the game in two different cultures, as an opportunity to make sure that the results would be generalizable and widely applicable. Then it was decided to take the opportunity to do it systematically and see whether there was an influence of cultural differences on the perception of the AR game.

Cultural issues could interact in complex ways in the design of AR games for mathematics schoolwork in elementary school, since children face different learning environments between different cultures. In China, children get used to having a lot of homework after school. According to a report (China Daily, 2018), Chinese kids from elementary and secondary school spend three hours on average on homework every day, which is three times as much time or even more than their counterparts in other countries. What's more, mathematics is also considered the most challenging subject by students, with 71.9% stating that they spend most of their time on mathematics homework (China Daily, 2018). The overwhelming homework can make children feel frustrated and stressed, resulting in negative attitudes towards homework as well as the learning experience (China Daily, 2018). Children often complain about schoolwork taking away their time for more enjoyable activities (Trautwein, 2007). In addition, in the home environment in China, parents are highly involved and controlling when it comes to their children's schoolwork. Parents are asked by teachers to supervise their children in finishing their homework. According to the same report (China Daily, 2018), over 80% of the parents feel exhausted from the homework of their children. Children from Western cultures spend fewer hours in school and devote less time after school to academic activities compared to Chinese children (Fuligni and Stevenson, 1995). The important cultural differences between the two cultures could influence children's perception of the AR game. We assumed that Chinese children would find the AR game that helps them finish maths exercises in a different way more enjoyable.

Besides the differences in the learning environment, children from different cultures play games in different formats. For instance, desktops are more prevalent in the West, mobile more in the East[7]. Subsequently game expectations could be different, where a mobile platform game may be more readily accepted in China, and also the aesthetical and game genre preferences could differ.

These are important cultural differences, and it is not unreasonable to assume that this could influence the perception of an AR game for homework. Thus, we proposed hypothesis 2:

H2. There are measurable differences in perceiving the AR game version over the paper version between children in China and children in the Netherlands in terms of (a) enjoyment, (b) desire to do the exercise in free time, (c) recommendation to others, (d) perceived fun of doing math, (e) likability of the experience.

3.5 User Study

Two user studies were carried out in China and the Netherlands to figure out whether the AR game was promising and whether this was culturally invariant or not.

3.5.1 Participants

In total, 38 children participated in two user studies with the consent from the teachers, one in China and one in an international school in the Netherlands.

China

20 Chinese participants (10 males and 10 females; Mean age = 8.20, SD = 0.62) were randomly selected from an average-level elementary school. Before the experiment, the teacher first briefly introduced the experiment procedure to the participants. Participants were then asked to answer a demographic questionnaire

[7] Source: gs.statcounter.com

independently, including the questions: 1) what is your age; 2) gender; 3) have you ever used AR before? 4) which digital games do you play? The demographic result of the participants in China is shown in Table 3.1. Three out of the 20 participants reported having used AR before. The most popular game among them was Minecraft, with 13 participants naming it as their most played game.

Table 3.1 Participant's characteristics in China.

		Numbers
Gender	Male	10
	Female	10
Age	7 years old	2
	8 years old	12
	9 years old	6
Usage of AR before	Yes	3
	No	17
Most played game	Minecraft	13

The Netherlands

In the Netherlands, 18 participants (10 males and 8 females; Mean age = 7.11, SD = 0.32) took part in the user study. They were students from one class in an international school who could speak English in the Netherlands. Before the experiment, the teacher first introduced the experiment procedure to the participants. The same demographic questions were presented to the participants. The characteristics of the participants are shown in Table 3.2. Among them, 3 out of 18 participants claimed that they experienced with AR technology before. Like the Chinese participants, 11 participants in the Netherlands said that Minecraft was their most played game.

Table 3.2 Participant's characteristics in the Netherlands.

		Numbers
Gender	Male	10
	Female	8
Age	7 years old	16
	8 years old	2
Usage of AR before	Yes	3
	No	15
Most played game	Minecraft	11

We noticed that these children, both in China and the Netherlands, had access to digital games, and the most common devices they used were mobile devices such as smartphones or iPads. Besides, these children from these two countries both like the game Minecraft, a sandbox game in a 3D world where players could explore, gather resources, craft, and fight.

3.5.2 Apparatus and Procedure

The mobile devices used in the study were Galaxy S8s with the Android operating system. We used Unity 3D[8] as the game engine to build the game, with the Vuforia[9] plugin for AR features.

Procedure in China

With the teachers' help, we randomly assigned the 20 participants into two equal groups (Group A and B). We used a within-subject design for the study, where

[8] **Unity 3D:** https://unity.com/

[9] **Vuforia:** https://developer.vuforia.com/

each group experienced the AR game exercise and the paper exercise in a counterbalanced order to avoid carry-over effects: group A played the game first and then did the paper exercise, group B did the paper exercise first and then played the game. All participants individually performed 10 mathematics exercises each time with roughly the same difficulty level, on paper or in the AR game, and vice versa. The exercises were chosen and modified from the maths textbook of grade 3 by the teacher. The paper exercises contained the same animals and assignments as the AR game so that purely the interactive AR aspects were tested instead of the fantasy narrative of anthropomorphic animals (which could communicate in human language and children could treat them as if they are human). Participants were told that there was no time limit, and they could finish the exercises at their own speed. After each round (paper exercise and AR game), each participant was asked to complete a questionnaire. At the end of the study, participants were interviewed regarding their preferences between the paper exercise and the AR game.

Procedure in The Netherlands

The 18 participants were randomly divided into two groups in the study in the international school in the Netherlands (Group C and D). Participants were divided into the experiment in groups of 9. Identical to the user study in China, each group experienced the AR game and the paper exercise in different orders. The paper version featured the same animals and exercises with roughly the same difficulty level as the AR game with exercises chosen from the mathematics textbook they were currently using.

After both paper and the AR game, participants were asked to complete the questionnaire. An extra scale Playful Experience of Need Satisfaction (PENS) (Rigby and Ryan, 2007; Ryan, Rigby, & Przybylski, 2006), which was developed based on SDT for assessing fun/enjoyment game experience, was filled in by the children after playing the AR game to measure their experience with the AR game. At the end of the study, participants were interviewed in groups with questions regarding their preference between the paper and the AR game, other possibilities in the game, other types of animals they want in the game, and the difficulty levels of the exercises in the game.

3.5.3 Measurements

There are five sub-scales in PENS, including competence, autonomy, relatedness, presence/immersion, and intuitive controls. According to Tyack and Mekler (2020), in previous studies, the dimensions of competence and autonomy were employed the most frequently with a percentage of 38.18% and 36.36% respectively in PENS. While the relatedness (24.55%), presence/immersion (25.45%), and intuitive controls (23.64%) were assessed less frequently. This might be caused that it remains unclear whether the sub-scales intuitive controls and competence measure different experiences (Johnson and Gardner, 2010; Johnson, Gardner, & Perry, 2018), and issues with some presence/immersion items have recurred across studies (Tyack and Mekler, 2020). Therefore, in our study, we only employed the sub-scales of competence, autonomy, and relatedness.

Motivation was measured by adapting the Intrinsic Motivation Inventory (IMI) (Ryan, 1982), which is a multidimensional instrument grounded on SDT for assessing motivation and the subjective experience of participants during an activity (Monteiro, Mata, & Peixoto, 2015). There are 42 items in total in IMI, which are available on the official SDT website[10]. However, many scholars did not validate the full IMI items (Tyack and Mekler, 2020). Some only assessed the interest/enjoyment dimension (e.g., Domínguez *et al.*, 2016; Vella, Koren, & Johnson, 2017; Vicencio-Moreira, Mandryk, & Gutwin, 2015). In our study, we also applied IMI mainly to measure the interest/enjoyment dimension.

The questions for assessing the desire to do the exercise in free time were adapted and revised from Peng *et al.* (2012) and Ryan, Rigby, & Przybylski (2006), including "G*iven the chance I would do this activity in my free time*". The

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[10] Center for Self-Determination Theory, 2019: https://selfdeterminationtheory.org/

recommendation to others was assessed by "*I would recommend this experience to my friends*" (Peng *et al.*, 2012). Lastly, self-made questions were developed by us to measure the likability of the AR game and the paper exercise, and to what extent did the game or paper exercise make maths more fun, using the statement, "*I like playing this game*" or "*I like doing this exercise*", "T*his game makes maths more fun*" or "*This exercise makes maths more fun*".

The Smileyometer designed for children was used to elicit children's opinions, which is a 5-point Likert scale and uses five smileys (Read, MacFarlane, & Casey, 2002). The answers of Smileyometer were recoded to 1 (strongly disagree) to 5 (strongly agree). See Figure 3.6.

The PENS questionnaire (Rigby and Ryan, 2007; Ryan, Rigby, & Pryzybylski, 2006) was used to measure the perceived autonomy, competence, and relatedness when playing the AR game. A 7- point Likert scale was used (1 = strongly disagree, 7 = strongly agree). An open-ended interview was conducted after finishing all the exercises and questionnaires, aiming to collect more in-depth feedback and suggestions from children for the future development of the AR game.

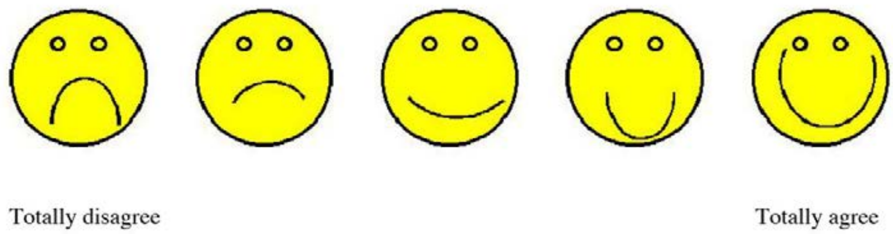

Figure 3.6 Smileyometer scale (Read, MacFarlane, & Casey, 2002).

We also gave a final score for the mathematics exercises for both the game and the paper versions for Chinese children as an in-game measure of mathematics learning since Chinese children were used to receiving scores on their homework performance. We did not give the final score for the mathematics exercises for children in the Netherlands.

3.6 Study Results

3.6.1 Mathematics Performance Test in China

A paired sample t-test was conducted to examine the final scores for the AR game and the paper exercise in China. There was no significant difference in the scores of the paper exercises (Mean = 8.40, SD = 1.60) and the game exercises (Mean = 8.25, SD = 1.59); t (19) = –0.43, $p = 0.673$. The results showed that the AR game had neither a negative nor a positive influence on children's performance in doing mathematics exercises. See Table 3.3.

Table 3.3 Participants' scores in game exercise vs. paper exercise in China.

Group	N	Mean	Std. Deviation	Std. Error Mean
Game exercise	20	8.25	1.585	0.354
Paper exercise	20	8.40	1.603	0.358

3.6.2 Motivation Test

China

When we compared the experience of the AR game with that of the paper exercises, significant differences were found in their likability of the experience (AR game: Mean = 4.60, SD = 0.60; Paper: Mean = 4.10, SD = 0.79; t(19) = 3.25, $p = 0.004$; Cohen's d = 0.71), desire to do it in their free time (AR game: Mean = 4.45, SD = 0.69; Paper: Mean = 3.60, SD = 1.14; t(19) = 3.10, $p = 0.006$; Cohen's d = 0.90), perceived fun of doing maths (AR game: Mean = 4.55, SD = 0.14; Paper: Mean = 4.00 SD = 0.19; t(19) = 2.98, $p = 0.008$; Cohen's d = 3.31), recommendation of the experience to others (AR game: Mean = 4.55, SD = 0.69; Paper: M = 4.10, SD = 0.91; t(19) = 2.65, $p = 0.016$; Cohen's d = 0.56), and enjoyment (AR game: Mean = 4.51, SD = 0.80; Paper: Mean = 4.03, SD = 0.59; t(19) = 4.17, $p = 0.001$; Cohen's d = 0.68). See Figure 3.7 and Table 3.4.

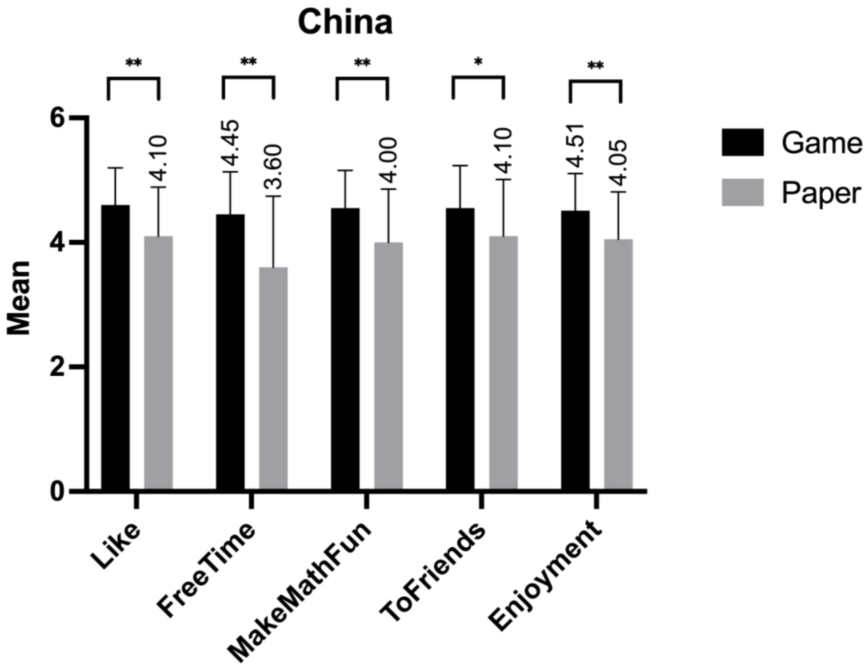

Figure 3.7 Motivation test in China.

Table 3.4 Comparison of the motivational factors in China (continued on the next page).

Items	Group	N	Mean	Std. Deviation	Std. Error Mean	Paired Differences Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)
Like	Game exercise	20	4.60	0.598	0.134	0.688	0.154	3.249	19	0.004**
	Paper exercise	20	4.10	0.788	0.176					
Free time	Game exercise	20	4.45	0.686	0.153	1.226	0.274	3.101	19	0.006**
	Paper exercise	20	3.60	1.142	0.255					
Make maths fun	Game exercise	20	4.55	0.135	0.605	0.826	0.185	2.979	19	0.008**
	Paper exercise	20	4.00	0.192	0.858					

Table 3.4 Comparison of the motivational factors in China (continued).

Items	Group	N	Mean	Std. Deviation	Std. Error Mean	Paired Differences				
						Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)
Recommend to friends	Game exercise	20	4.55	0.686	0.153	0.759	0.170	2.651	19	0.016*
	Paper exercise	20	4.10	0.912	0.204					
Enjoyment	Game exercise	20	4.51	0.593	0.133	0.534	0.119	3.876	19	0.001**
	Paper exercise	20	4.05	0.763	0.171					

** for significant at the p < 0.05 level*

*** for significant at the p < 0.01 level*

The Netherlands

Whereas the children in China already evaluated the AR game very positively, the international school children in the Netherlands rated it even higher, leading to a strong negative skew and ceiling effect for many of the motivational correlates of the AR game (likability: Mean = 5.00, SD = 0.00; desire to do the exercise in free time: Mean = 4.67, SD = 0.97, skewness = −3.58; perceived fun of doing math: Mean = 4.78, SD = 0.94, skewness = −4.24; recommendation to others: Mean = 4.72, SD = 0.96, skewness = −3.89; enjoyment: Mean = 4.71, SD = 0.51, skewness = −1.82).

Due to the strong negative skew and ceiling effect, we decided to perform Wilcoxon signed rank tests. The professed desire to continue playing the AR maths exercises in the free time was significantly higher than the desire to continue doing the paper exercises (resp. Mean = 4.67, SD = 0.97 vs. Mean = 4.18, SD = 1.33; $Z = -2.03$, $p = 0.042$; Cohen's d = 0.42). After playing the AR game, the participants were also more inclined to recommend it to others than the paper exercises (resp. Mean = 4.72, SD = 0.96 vs. Mean = 4.18, SD = 1.24; $Z = -2.41$, $p = 0.016$; Cohen's d = 0.49).

All other tests were non-significant: the likability of the experience (AR game: Mean = 5.00, SD = 0.00 vs. Paper: Mean = 4.71, SD = 0.69; $Z = -1.63$, $p = 0.102$), perceived fun of doing maths (AR game: Mean = 4.78, SD = 0.94 vs. Paper: Mean = 4.65, SD = 0.70; $Z = -1.86$, $p = 0.063$), and enjoyment of the experience (AR game: Mean = 4.71, SD = 0.51 vs. Paper: Mean = 4.68, SD = 0.578; $Z = -0.48$, $p = 0.635$). 17 participants finished in the entire questionnaire. See Table 3.5 and Figure 3.8.

Table 3.5 Wilcoxon signed ranks test in the Netherlands.

Pair	Test Statistics	
	Z	Asymp. Sig. (2-tailed)
Like Game vs. Like Paper	-1.633	0.102
Free time Game vs. Free time Paper	-2.032	0.042*
Make maths fun Game vs. Make maths fun Paper	-1.857	0.063
Recommend to friends Game vs. Recommend to friends Paper	-2.410	0.016*
Enjoyment Game vs. Enjoyment Paper	-0.475	0.635

** for significant*

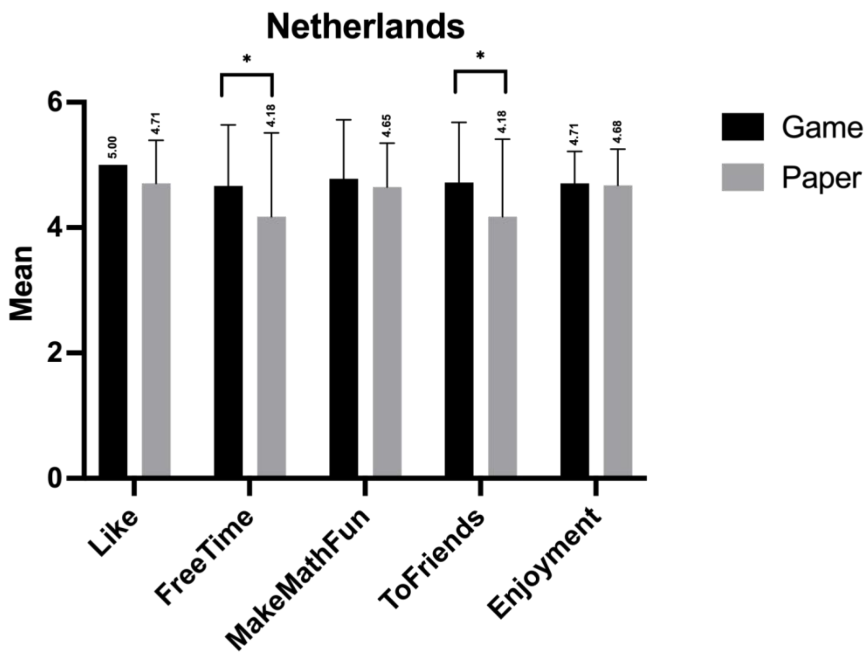

Figure 3.8 Motivation test in the Netherlands.

It is also remarkable that the standard deviation, almost for all questions and in both countries, was much higher for the paper exercise than for the AR game. One potential explanation could be that paper exercises worked well for some children but posed serious difficulties for others. The low standard deviation for the AR game could be a novelty effect: children did not know much about it and had no enough experience to develop nuances and differentiate, but were attracted by it.

3.6.3 Cultural Differences

Both two cultures rated the AR game very positively. We found no interaction effect between culture and the likability of the game, desire to do the exercise in free time, perceived fun of doing math, recommendation to others, and enjoyment over the paper version. Compared to Chinese children, the international children significantly liked the AR game more than the paper exercises ($F(1, 35) = 9.11$, $p = 0.005$). See Figure 3.9.

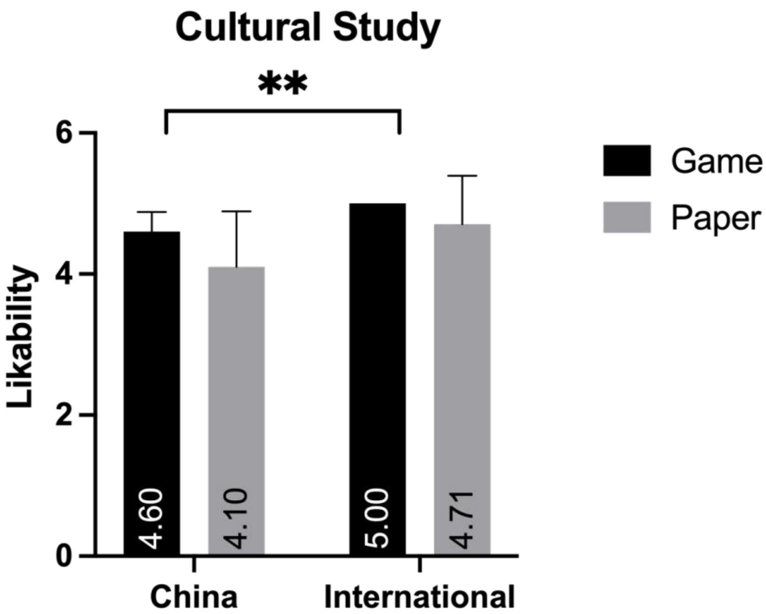

Figure 3.9 Cultural differences.

3.6.4 Qualitative Evaluation

We got more positive feedback from the interview. In the user study in the international school, all of the 18 participants reported that they preferred the AR game to the paper version, as indicated by comments such as “it’s like fun, and you can feed, and you can do a lot of different stuff with the animals. And you can even move them” (participant 1), “because it was good, you can do maths and you can see the real animals” (participant 2), “because you get to learn more, animals get to pop out in 3D” (participant 3), “because there are a lot of different options, and I can really see the animals in 3D, I haven’t seen them in real life. It gives you a chance to see the animals in real life and then you can feed and do a lot of interesting stuff” (participant 4), “because it’s really cool, like you scan the animal and it comes to you” (participant 5), “I like the game because you don’t have to do only one thing, but you can do many many more things” (participant 6), “I like the multiple possibilities” (participant 7), and “I like it because we can make maths more fun, we can give the animals food and I also like the maths questions, there are a bit easy but also fun at the same time” (participant 8). One participant gave negative feedback on the scanning of the AR animals in See Me Roar, stating that “changing the animals is the only hard thing there” (participant 10).

In the user study in China, 18 out of 20 participants reported that they preferred the AR game to the paper version. The typical positive comments obtained by the participants were “the game was more 3-dimensional” (participant 19), “the game was more realistic” (participant 20), and “it was more vivid” (participant 21). Conversely, one participant expressed negative feelings on the AR game, “it was troublesome to scan the paper and see the animals” (participant 22). Another participant (participant 23) stated that there was no difference between the AR game and the paper version.

Participants would like to have more possibilities in the AR game, for example, “I want it to not to move so slowly, I want to make it move faster, and sometimes there can be interesting with more controls” (participant 1), “we can even have other animals in it” (participant 11), “we can also make the animals make babies” (participant 6), “I want it not to disappear because I want to see it all the time” (participant 7), and “I want to hear the animals make noises” (participant 8).

Participants had different preferences regarding the difficulty levels of the exercises. Some expressed that they would like harder exercises, “the exercises can get harder so you can practice new strategies” (participant 12), “I want the exercise to be harder so it can be more challenging” (participant 13), and “I want it to be hard and difficult so we can get better and faster” (participant 14). On the other hand, some participants would like the exercises to be easier, “I want easy exercises because it’s better to get started with the easy questions” (participant 15), “I like easy questions because I don’t want to do harder stuff” (participant 16), and “I like it to be easy, if the maths is too tricky, I don’t really like it because then you need to think too much” (participant 17).

Participants would like to see more types of animals in the game, including sea creatures, ancient animals they have never seen before, and others. “We could do some scary animals, like animals in the sea, or flying, or maybe some dinosaurs. You can also make a 3D one, which is also about buildings and places, just in case people want to see it and never see it before in 3D. Then they can see it” (participant 14), “I want more animals, it could be a really funny creature” (participant 17), “Ancient animals. Because none of us ever saw them, it will be more interesting” (participant 18), “I would like more animals, I can take home and wild animals” (participant 10), “I would like a bunny and the unicorn as animals” (participant 6), “I want ancient animals which I’ve never seen, maybe dinosaurs” (participant 12), and “I want more animals because we can have more fun, and they can be like a cat, dog, rabbit or something else” (participant 4).

3.6.5 PENS Questionnaire

The result of the PENS questionnaire was considered as unreliable in this study since most participants (15 out of 17) chose “strongly agree” with each statement using the 7-point Likert scale, including negatively coded statements. Although participants rated the game highly in the PENS questionnaire, the interview results revealed deeper insights. When asked about other possibilities in the game, participants expressed their different needs for the same game control. For example, one wanted the animals to move faster and the other wanted slower. The children also expressed that they would like to experience richer interactions with the animals. For example, the animals could make sound as reactions or to let animals have babies. They were also looking for more types of animals in the game, including the sea creatures, ancient animals they have never seen before, wild animals, and fantasy animals such as unicorns. Participants reported different preferences regarding the difficulty levels of the maths exercises. Some expressed that they would like harder exercises to practice their skills to learn better and faster, and to feel more challenging. Conversely, some participants would like to start with easy exercises because they were not willing to deal with tricky exercises. It was also observed that during the game, participants shared their screens with others and discussed the game elements frequently. For example, they would show that their animals were walking on the table or books of others, or animals were eating on their hands.

3.7 Discussion

From the results we can see that compared to the paper exercise, the AR game increased all the motivational factors for children in China. Hypothesis 1 is confirmed. Children from the Netherlands also significantly increased their desire to do the exercises in their free time and the recommendation of the experience to others by performing the AR game than the paper version. Regarding hypothesis 2, no significant difference existed between Chinese children and the international children in the Netherlands, except for the likability of the game and the paper, where international children significantly liked the AR game more than the Chinese children. No significant difference was found in the in-game learning performance (the number of items that were answered correctly) between the AR game and the paper version. The interview results showed that children were attracted by the AR animals and the rich interactions within the game. Feeding and helping animals while doing mathematics helped to immerse children into the game world and improved their learning process.

What was especially noteworthy and came as a surprise to us, is just how much the children liked the AR game. So much in fact that it makes us a bit incredulous as to the veracity of the results. To our estimation, the game was barebones and lacked a lot of engaging game mechanics and design features. It has not yet been designed to really stimulate competence, autonomy, and relatedness, and the learning content was not well integrated with the game mechanics. For all intents and purposes, it should score worse than many other serious games which fail to be motivating (Wouters *et al.*, 2013). It is tempting to think the design of AR animals walking over one's textbook is indeed by itself incredibly motivating for children of elementary school age. However, it is also likely that this statistic is at least partially influenced by both novelty and Hawthorne effects.

The SDT-based PENS questionnaire failed to give reliable results in this study, but that was most likely a problem of the children's abstraction level during the form-filling, not a problem of the SDT concepts themselves. From the qualitative results, we recognized the SDT concepts, namely autonomy, competence, and relatedness, behind the children's words and behaviors. For example, children perceived the difficulty levels of the exercises differently based on their own abilities and skills, and they also expressed "so we can get better and faster", which were referring to the perceived competence; Children provided ideas related to the perceived autonomy with "more types of animals", "richer reactions from the animals", and "different controls of the game". During the study, it was also observed that children tended to share their experience (shared their screens) and help each other play the game, while they also compared with each other in the finishing speed and the rewards they could get, which were related to the perceived relatedness.

Concerning the measurement methods, even though a literature search indicated that Likert-scales and the Smileyometer were suitable for children, we noticed many children rating both positive and negatively worded statements with "strongly agree" and tending to choose the most positive score in the

Smileyometer scale. This means that in their enthusiasm or desire to please the experimenter they did not read all the questions correctly. Children tend to provide the answers that they think the experimenter asking the question wants (Hall, Hume, & Tazzyman, 2016). Both quantitative and qualitative measures that tease out more useful or constructive critical reflections should be devised in our future studies.

3.8 Conclusion

To conclude, the results of the study indicated that in general, the AR game prototype of See Me Roar received very good evaluations for enjoyment, desire to do in free time, perceived fun of doing math, likability, as well as recommendation to others. The AR game achieved significantly higher ratings on these subjects by the participants over the paper version. It could be used to help children to do mathematics school-work in a more playful and fun way. The AR game concept with animals walking over ones' textbook could be globally accepted by both children from the Eastern and Western cultures.

This study is the first step in our research, proving the positive motivating effects of the working prototype of the AR game for children from different cultures. Our initial research plan was to have a base version of the game without any fills, and then we could improve the base version to better enhance children's learning motivation step by step with the competence, relatedness, and autonomy-inspired features. However, since the results of the current game already scored so highly, we changed our plan into designing a more or less new game for every iteration, but taking the ideas generated from each iteration to a next game idea. We would keep developing games based on SDT in our research and applying the research through design method, augmenting the basic game idea to include game mechanics to stimulate feelings of autonomy, competence, and relatedness. In the next chapter, the application of this method continues with the design of a competence-inspired AR serious game.

CHAPTER

FOUR

DESIGN AND EVALUATION OF A COMPETENCE-SUPPORTIVE AR SERIOUS GAME

Chapter 4: Design and Evaluation of a Competence-Supportive AR Serious Game[11]

4.1 Introduction

Our study applies a research-through design method where we go from a base game to three studies based on SDT, together with PLEX as mentioned in the first chapter. In Chapter 3 we explored the game concepts together with children and came up with the current base game, See Me Roar, which received a good evaluation with the concepts of animals and food in two different cultures.

We iterated the base game with competence-inspired features. We explored and investigated two common interaction techniques in AR environments: a real-world tangible interaction and a screen-touch interaction. The real-world tangible interaction was done through children's manipulation of a physical textbook, the screen-touch interaction through a digital touchscreen. Moreover, we deployed two feedback mechanics: non-diegetic feedback (where the feedback was delivered through a 2D progress bar) and diegetic feedback (where the feedback was presented with additional 3D animations). This exploration and investigation fit in the larger context of this thesis: to gain a deeper and fuller understanding of how to incorporate AR-specific elements in serious games to enhance children's learning motivation and experience.

To explore these two interaction styles and two feedback mechanics, we first reviewed current studies on AR games related to their motivational effects. Then we presented a set of AR game prototypes and elucidated the design decisions

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[11] **Based on:**

Jingya Li, Erik D. van der Spek, Jun Hu, and Loe Feijs. (2019). Turning Your Book into a Game: Improving Motivation through Tangible Interaction and Diegetic Feedback in an AR Mathematics Game for Children. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (pp. 73-85).

based on participatory design sessions and previous user tests. These game prototypes shared a commonality with general serious game design but differed in the mentioned interaction styles and feedback mechanics. By comparing them through an experimental study, we could investigate the way children were motivated in the AR experience. To conclude, we generalized our empirical findings and proposed recommendations aimed at helping designers in making appropriate design choices in AR to support the playful and enjoyable experience for children.

4.2 Related Work

In Chapter 2, we explained our theoretical framework as we mapped the challenge and the completion in PLEX to the competence within SDT. In this chapter, we further investigate which types of AR features can be inserted into the game to utilize the unique advantages that AR affords.

4.2.1 Interaction Types

One of the important features of AR is that it enables real-time interaction, combining the physical object and virtual world (Azuma, 1997). The interaction between the user and the AR application is one of the main things to consider when developing AR for education (Hantono, Nugroho, & Santosa, 2018). However, previous studies on AR have mostly focused on displaying additional information on top of the real world without specifically concerning how users would interact with the system (Seo and Lee, 2013). In AR environments, users can interact with the game using different interaction techniques (Radu, MacIntyre, & Lourenco, 2016). Screen-touch is one common interaction technique used in AR games for children (e.g., Chen, Chou, & Huang, 2016; Tobar-Muñoz, Baldiris, & Fabregat, 2017), allowing them to select which item they wish to act upon by touching on the digital screen of the mobile device with fingers (Radu, MacIntyre, & Lourenco, 2016). This kind of interaction is based on the virtual content, whereas it is suggested that AR interaction should be appropriately designed and created to support seamless interaction between the virtual and physical world (Billinghurst, 2002; Billinghurst, Clark, & Lee, 2015; Seo and Lee, 2013; Zhou, Duh, & Billinghurst, 2008). Tangible interaction has the potential to offer a more entertaining experience to users with a series of intuitive and natural interactions and is easier to use since the physical objects used have familiar properties (Zhou *et al.*, 2004; Zhou, Duh, & Billinghurst, 2008). A number of previous studies have applied tangible interaction tools such as paddles and cubes with paper-based documents like storybooks, aimed at making children enjoy more and perceive more fun (e.g., Hornecker and Dünser, 2007; Tomi and Ramble, 2013; Xu *et al.*, 2011; Zhou *et al.*, 2004). However, challenges and limitations remain in these tools. For example, paddles are effective and frequently used for simple manipulations, but are unable to support more sophisticated and direct interaction with virtual content (Seo and Lee, 2013). Children would expect the virtual objects to react and behave analogously to the physical objects in the real world (Hornecker and Dünser, 2007). Consequently, tangible interaction tools may confuse children what it is in their actions that makes the system react (Hornecker and Dünser, 2007). This aspect should be addressed when designing tangible interaction for children. Besides these major tangible interaction tools, the textbook itself can also be a tangible tool to enhance the user's interaction with different interactive features present in the book (Dünser, Grasset, & Billinghurst, 2008). In the study of Billinghurst, Kato, & Poupyrev (2001), they explored the design space for the interaction in a real book and gave an example that a user could tilt the book page to control the gravity of some objects. However, the interaction with the book has not been explored and studied in detail to refine the design space. What's more, the motivational effect of this kind of interaction on children has not been fully explored and empirically investigated. In addition, previous work did not focus on school textbooks, which could also be valuable since they are widely used by children during learning activities.

4.2.2 Feedback Mechanics

In traditional video games, players should be given appropriate and clear feedback at an appropriate time during the game to keep them motivated at a high level (Park, Abirached, & Zhang, 2012; Sweetser and Wyeth, 2005). For example, the progress bar in the Clash of Clans[12] (left) and Brawl Stars[13] (right) in Figure 4.1.

Figure 4.1 Traditional games with progress bar (Clash of Clans and Brawl Stars).

Feedback lets players know where they are in the game process, which is even more important for learning games (Annetta, 2010). Hence, feedback mechanics on the progress should be considered carefully in children's learning games. The vertical progress bar has been commonly used in traditional serious game design. For example, in the study of Park, Abirached, & Zhang (2012), the player's progress in the game was represented by a series of symbols within a vertical bar. Observations from the same research have shown that progress feedback is important and used by children to determine how many actions they still need to perform to finish the current round of game play (Park, Abirached, & Zhang, 2012).

This type of progress bar called a non-diegetic element, which is not visible inside the spatial game space or the fictional game world (Brook, 2017). Non-diegetic game elements, such as the health bars and the objective indication, take

[12] **Clash of Clans:** https://supercell.com/en/games/clashofclans/

[13] **Brawl Stars:** https://supercell.com/en/games/brawlstars/

part in the game action and deliver feedback or relevant information to players (de Araujo and Souto, 2016). Figure 4.2 shows the classification model consisting of the non-diegetic, diegetic, meta, and spatial dimensions of visual feedback (Brook, 2017).

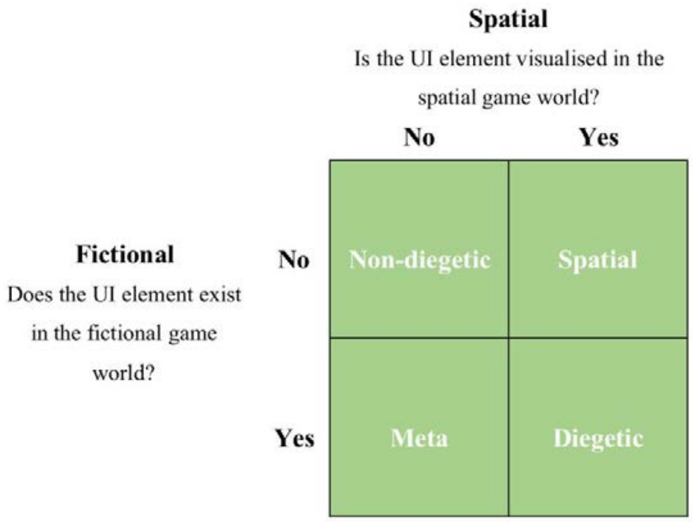

Figure 4.2 Visual Feedback Classification Model (Brook, 2017; Fagerholt and Lorentzon, 2009).

The non-diegetic progress bar has also been applied in AR games. For example, in the user study of a multi-player AR game for swimming pools reported by Oppermann, Blum, & Shekow (2016), a 2D progress bar was presented on the digital screen providing game feedback to children (see Figure 4.3). Their study indicated that the use of the 2D progress bar as feedback of the game process was not sufficiently obvious to children in the AR experience (Oppermann, Blum, & Shekow, 2016).

Unlike non-diegetic feedback, feedback that is both visible inside the spatial game space and the fictional game world can be seen as diegetic feedback (Brook, 2017). Diegetic game elements are a part of the game world where players need to observe the environment in order to perceive the information (Brook, 2017). For example, in-game devices or objects, such as health pickups, a watch, or a diary, are frequently used to provide the player with feedback information (Brook, 2017). Figure 4.4 shows an example. AR technology is characterized by its 3D registration of virtual and physical objects (Azuma, 1997), which can be utilized to develop, in a sense, diegetic feedback to show progress in a more obvious way. However, its motivational effect compared to non-diegetic feedback remains unclear.

Figure 4.3 AR educational games with progress bar in the bottom (Oppermann, Blum, & Shekow, 2016).

Figure 4.4 Health pickups in Fortnite[14].

[14] **Fortnite:** https://www.epicgames.com/fortnite/en-US/home

4.2.3 Research Questions

In this study, we applied SDT to understand how different interaction types and feedback mechanics in the AR game influence children's learning motivation and experience. Within SDT, competence refers to the perceived extent of one's own interactions as the cause of desired consequence in the environment and thrives when the player is provided with direct and positive feedback (Deci and Ryan, 2002; Ryan and Deci, 2000a; Ryan, Rigby, & Przybylski, 2006; Ericson, 2016). We designed two different prototypes in AR, which were digital screen-touch interaction and real-world tangible interaction. Secondly, we designed two different feedback mechanics in AR, investigating the effects of non-diegetic and diegetic feedback on children's motivation. We aimed to answer the first research question of this thesis:

RQ1. How to incorporate AR-specific elements in serious games based on notions of perceived competence in Self-determination theory to enhance children's learning motivation and experience?

- 1.1 How can we integrate different types of challenges in AR serious games for children, and which of these types work better?
- 1.2 How can we integrate different types of completion in AR serious games for children, and which of these types work better?

4.3 Design Process

In this section, we explained the game concepts and how the outcomes of previous studies affected our design decisions.

4.3.1 Game Concepts

Iterated from the base-game prototype in Chapter 3, we designed and developed the AR game for elementary school children to practice maths arithmetic. In the current game, when children scan the paper containing a background image as a marker and an exercise, a virtual animal and different food carrying answers on top of them will show up. In Chapter 3, the gaming elements (animal eating food) and the learning content (the exercises) were separate, while the learning goals in a serious game should be integrated into the game play (Camps-Ortueta *et al.*, 2019). Therefore, the goal of the current game is to navigate the animal to eat the food carrying the correct answer for the exercise. The maths exercises shown on the paper included addition (e.g., 26+9=?), subtraction (e.g., 47-18=?), and simple multiplication (e.g., 3x4=?). Children could do the calculation first and then navigate the animal to a corresponding answer.

Then we designed the game into different versions with the screen-touch interaction used in Chapter 3 and tangible interaction based on the features that AR affords, namely intuitive interaction between the real objects and virtual objects. A 2D progress bar was applied to provide non-diegetic feedback as in previous studies. We also designed a 3D progress map to represent the diegetic feedback with the 3D registration of AR affordance. Besides the number of dimensions, we also embedded the 3D progress map in the game narrative (detailed concepts would be explained later). Overall, four new versions of the AR game with two types of different interactions and two types of feedback mechanics are listed in Table 4.1.

Table 4.1 The four conditions.

		Interaction Types	
		Screen-touch	Tangible
Feedback Types	Non-diegetic	Screen-touch with 2D progress bar	Tangible with 2D progress bar
	Diegetic	Screen-touch with 3D progress map	Tangible with 3D progress map

4.3.2 Tangible Interaction

From the results of the user studies in Chapter 3, we found that children expected more intuitive interactions with virtual objects. They would use their hands to touch the virtual animals, moved their books from left to right, or raised the books higher to see what would happen to the animals. Hence, in the new version we would explore more intuitive interactions between children and the physical books with tangible interaction. See Figure 4.5a.

Figure 4.5 Experiment conditions: (a) tangible; (b) screen-touch.

In the current version, children also scan the physical paper to see the animals and food carrying answers. However, here we turned the paper itself into the interface with which to control the game. We calculated the change of the angles between the AR camera and the paper interface and mapped it onto the animals in the 3D coordinate system in real-time. Children need to rotate the paper to turn the animal (see Figure 4.6a) and tilt the paper in order to make the animals move (see Figure 4.6b).

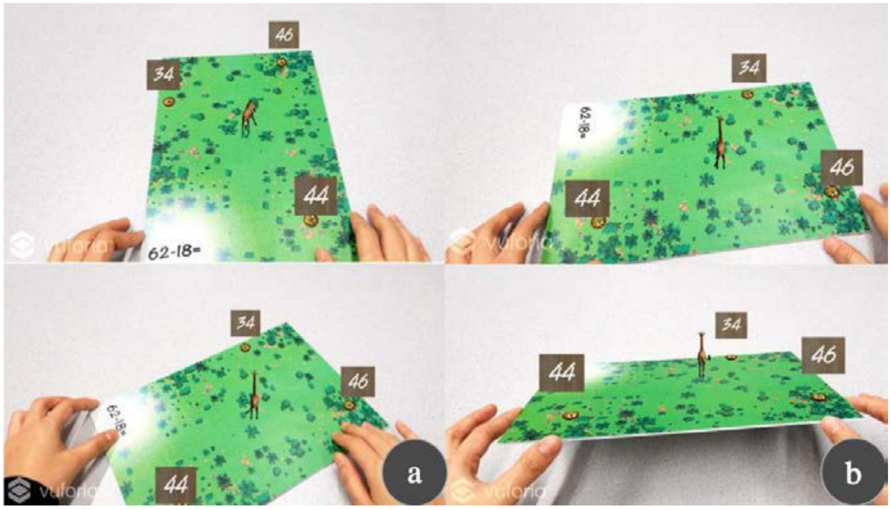

Figure 4.6 Tangible interaction: (a) rotating; (b) tilting.

To be more specific, the user could rotate the physical paper from left to right or vice versa to make the animal face into the desired direction (Figure 4.7). By lifting the paper, the user could control the speed of the animal. For example, if the user lifts the paper with 0 to 15 degrees, the animal will start to walk ($a>0$). If the user lifts the paper more than 15 degrees, the animal will speed up from walking to running. This reaction simulates rolling a ball on a downhill slope in the real world. Similarly, if the user lifts the paper from the opposite side, its moving speed will slow down until the animal stops ($a<0$), which simulates the movement on an uphill movement in the real world.

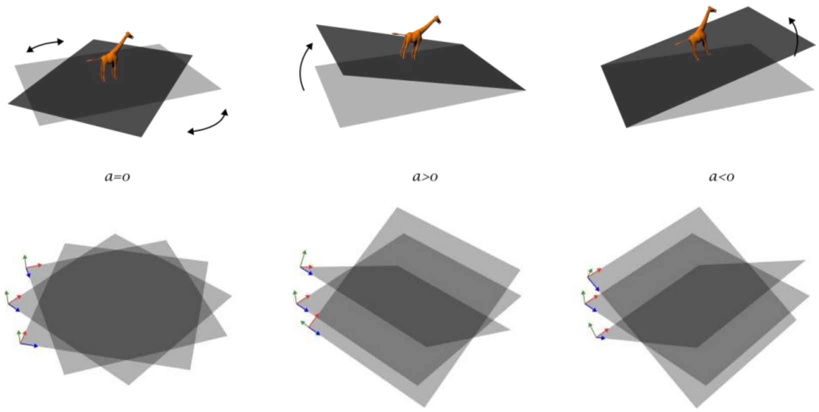

Figure 4.7 Reactions of the virtual animals according to different actions: turning; speeding up; slowing down.

As far as we could find, using a textbook as the game controller is still novel in the field of serious AR games for learning. Note that, because scanning the textbook occasionally gave problems with AR marker recognition in a real-world setting (classroom, home, or library), we switched over to an image on a single paper for the purpose of this new study. The concept of the game is still to gamify an existing maths textbook.

4.3.3 Screen-Touch Interaction

In the base-game prototype, children had no difficulty in interacting with the animals with the screen-touch technique. Like the base-game prototype, in this version, children would guide the animals to eat the food with screen-touch input by touching on top of the food on the screen. Then the animal would run directly to the touched food. They could also touch on another food to change the answer. The speed of the animals is the same as the running speed in the tangible version, and the interaction with the physical paper would not affect the actions of the animals in this version. See Figure 4.5b.

4.3.4 2D Progress Bar

In the version with the 2D progress bar, after the animal eats the selected food, children would see their performance immediately on the screen in an explicit way: if the answer is correct, a golden circle would appear, while the wrong answer would lead to a red circle. At the end of the game, children could see 10 golden circles if they find all the correct answers (see Figure 4.8a).

4.3.5 3D Progress Map

In Chapter 3, we found that children were excited about the rewards (food) they collected in the base game. However, these rewards were simple game objects that could be spawned in any digital game, and therefore did not capitalize on the more unique AR affordance of a mixed reality game world. Children also expressed that they did not want the animals to disappear after finishing the exercises. Therefore, in this new version, we introduced an interactive progress map. After the animal eats the correct answer, children could see the same animal appear on the physical map. If the answer is wrong, children could not find the animal anywhere. Children could check the map anytime they want during the game.

The 3D progress map capitalizes on the unique affordance of AR where children can move the physical object (the map) to view the AR animals from different angles in the real-world perspective. In AR games, the players' experience could be enhanced by the combination of real and virtual elements rather than focusing entirely on digital technology, for example using a real paper map to help children orient themselves in the real world (Wetzel *et al.*, 2008). This concept could also be extended to include support for physical elements such as cups, glasses and etc. (Wetzel *et al.*, 2008). In addition, previous studies have shown that students expressed the need to see realistic animation elements in AR world (Cai, Wang, & Chiang, 2014). The inclusion of animation in AR settings could enhance students' interest (Gün and Atasoy, 2017). Therefore, in the 3D progress map, all the animals are animated such as eating, swimming, etc. At the end of the game, children could see 10 animated animals if they answer all the exercises correctly (see Figure 4.8b).

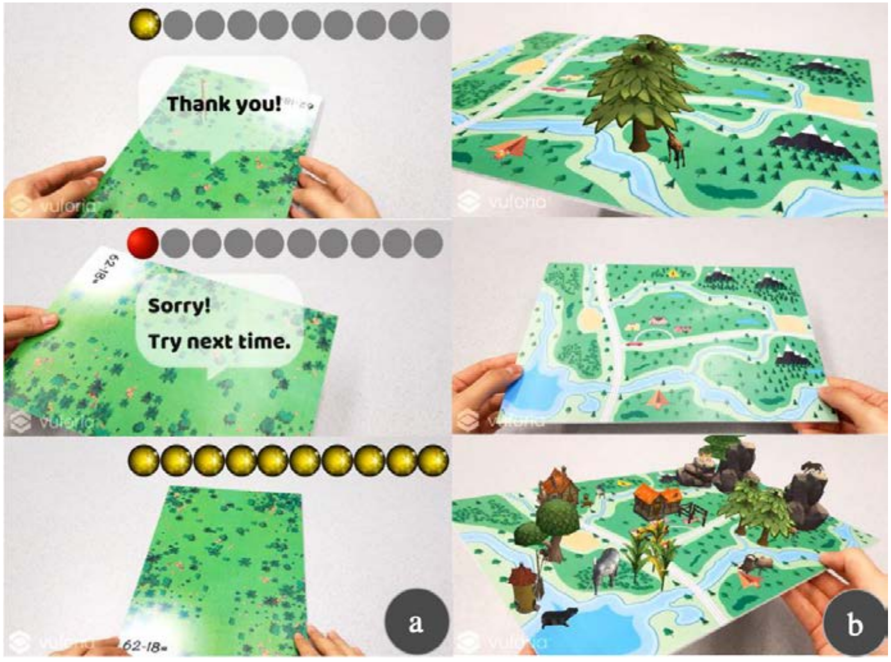

Figure 4.8 Different feedback mechanics: (a) progress bar; (b) progress map.

4.4 User Study

To explore the impact of the different interaction techniques and feedback mechanics in AR games on children's learning motivation and experience, we conducted an experiment with a mixed design. Different interactions were treated as a within-subject variable. This separation could help us understand which types of interactions would work more effectively in motivating children to do given exercises. Different feedback mechanics were treated as a between-subject variable since its effects might carry over to the other condition in a within-subjects test.

4.4.1 Participants and Procedure

A total of 32 children who participated in the study (16 of whom self-identified as male and 16 of whom self-identified as female) between the ages of 7 and 8 (Mean age = 7.72) were recruited from the local city library in the Netherlands and from personal acquaintances of the researchers. All children participated in the study with both their parents' consent (informed consent form signed) and their own willingness. All of them reported having used smartphones and never or rarely used AR before. No other demographic data were gathered. The experiment was conducted in a real-world setting. To be more specific, on the desk in the library where children could read books or on the desk at children's home. Parents were all present in the same room without intervening in the study procedure. The initial goal of this game was to let children practice maths in after-school activities, thus we chose these locations to make children feel safe and behave naturally. We assigned children to different condition groups randomly and each child was exposed to two different types of interactions and answered the same questionnaire with randomized questions after each interaction in a counter-balanced manner. At the end of the experiment, we conducted a short interview with each child.

4.4.2 Settings and Apparatus

The game prototypes were developed with Vuforia in Unity 3D. The experiment materials included a smartphone (Samsung Galaxy S8), a flexible phone-holder, and papers with different images and exercises (see Figure 4.9). In the within-subjects study, participants finished 10 exercises with one condition and the other 10 exercises with the second condition. These two sets of exercises were roughly the same difficulty level with the same operators but different numbers, including 4 additions, 4 subtractions, and 2 multiplications selected from a Dutch elementary school maths textbook for group 5.

Figure 4.9 Settings and apparatus.

4.4.3 Measurements

Player Experience of Need Satisfaction Questionnaire (PENS)

The PENS scale (Deci and Ryan, 1985; Rigby and Ryan, 2007; Ryan, Rigby, & Przybylski, 2006) was developed based on SDT for assessing the game experience. We included scales for competence to assess the perceived efficacy playing the game (3 items, e.g., "My ability to play the game is well matched with the game's challenges"), autonomy to assess the sense of self-determined behaviors (3 items, e.g., "The game provides me with interesting options and choices"), and relatedness to assess the sense of social connections (3 items, e.g., "I find the relationships I form in this game important") from PENS. We also measured the game enjoyment of children with 2 items adapted from IMI (Ryan, 1982) (e.g., "I enjoyed playing this game very much"). The PENS and IMI statements are originally rated on a bipolar 7-point Likert scale where 1 represents "strongly disagree" and 7 represents "strongly agree". In Chapter 3, we found that 7-8-year-old children had difficulty in understanding bipolar scales and especially the double negative that arises from a negatively worded statement with a bipolar answer (Li *et al.*, 2018). In addition, children often only picked the extreme answers, possibly indicating difficulty in understanding written nuances in emotions. Subsequently, we looked for ways to improve the granularity of the responses.

Animated Scales

In the CCI research field, the Smileyometer scale is one of the most used items that can help children to identify their feelings or opinions (Yusoff, Ruthven, & Landoni, 2011). This scale has been applied as an alternative to the Likert-scale to collect reliable quantitative data from children (Wu *et al.*, 2013). Existing research on the Smileyometer indicates that this tool performs the best for children to compare ratings between different conditions (Radu, 2016; Read, 2008). However, previous studies have pointed out that the Smileyometer is reliable for children aged 10-12-year-old, while younger children may have a greater tendency to select the highest ratings and so the data had little variability (Li *et al.*, 2018; Read and MacFarlane, 2006; Read, MacFarlane, & Casey, 2002; van Dijk, Lingnau, & Kockelkorn, 2012; Yusoff, Ruthven, & Landoni, 2011). Some studies suggested using only variations of smiling faces, or improving the graphical aesthetic of the design by making it more colorful and visual or by using cartoon-style emoji designed for children to elicit more nuanced responses from children (Hall, Hume, & Tazzyman, 2016). However, the proposed alternatives have only been proven reliable for children aged 9-11-year-old (Hall, Hume, & Tazzyman, 2016). The fun semantic differential scale developed by Yusoff, Ruthven, & Landoni (2011) combines photographs and semantic differential scales for young children. Conversely, this scale contains photographs for specific expressions (e.g., “happy” or “sad”), which are not applicable in our study.

Thus, to avoid the risk of collecting only extreme positive results with little granularity and to improve the construct validity, we changed the scale from a bipolar scale to a unipolar one, effectively turning the three statements of each psychological need into six statements, three positive and three negative ones (e.g., “The game let me do interesting things” and “The game let me do boring things"). These questions were randomized in the questionnaire. Furthermore, to aid 7-8-year-old children to select more nuanced answers, we developed an animated scale using the AR animated cartoon characters Memoji available from iOS system[15], which are more colorful and visually expressive than characters used in previous research (e.g., Hall, Hume, & Tazzyman, 2016; Yusoff, Ruthven, and Landoni, 2011). The facial expressions and movements were recorded by the acting of two Dutch actors. See Figure 4.10.

Figure 4.10 Recording with two actors.

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[15] **Memoji:** https://support.apple.com/en-us/HT208986

These facial expressions and movements were transferred to animations by the iOS system directly. The facial expressions were associated with the intensity of the movements (e.g., "strongly agree" with a positive statement: big smile and strong nodding; "slightly agree" with a negative statement: a weak sad face and slight nodding). Figure 4.11 shows two examples.

The animated scales include different characters with different genders, races, and appearances since children may tend to choose the character that matched their gender (Wu *et al.*, 2013). See Figure 4.12. Children could select one character and then use the same character during the entire questionnaire.

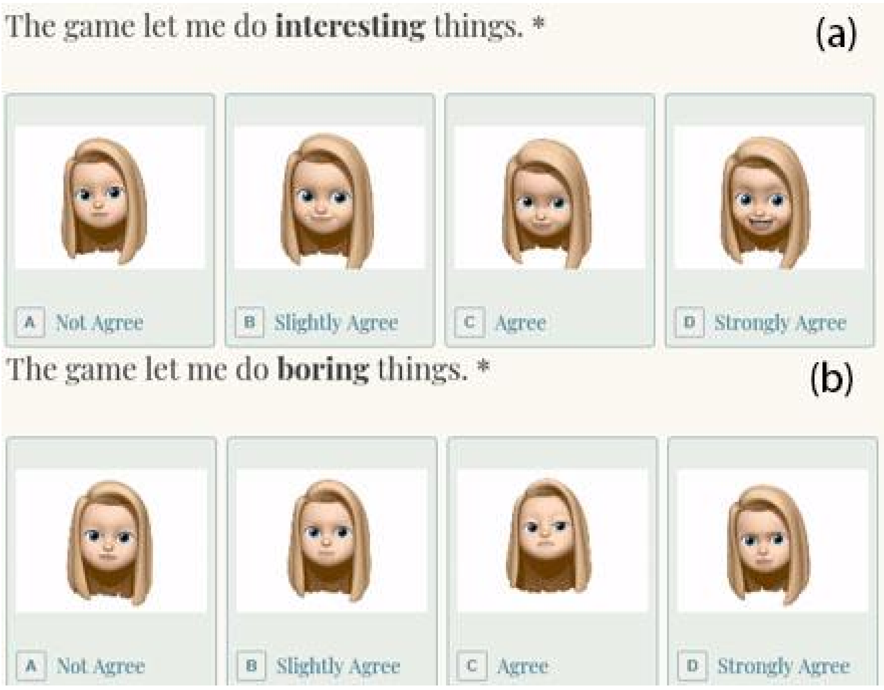

Figure 4.11 Examples of the animated scales: (a) positive statement; (b) negative statement.

Figure 4.12 Different characters in the animated scales.

We ran a pilot study with the animated scales. Children played two games, one entertainment game, viz. Minecraft, and one screen-touch AR game to do maths exercises (base-game in Chapter 3). After each play, they answered the questionnaire using the animated scales. Children said that they could understand the meaning of the animations and rated Minecraft higher than the AR game in some questions (e.g., “The game was fun to play”).

Based on their feedback, we modified some statements in the original scales to ensure the understanding of the statements in the questionnaire (e.g., “I experienced a lot of freedom in the game” to “I could do what I want in the game”). Besides the data collected from the questionnaire, children were also interviewed afterwards about their preferences of different versions, the reasons, and other improvements for the game. In addition, children’s behaviors were observed and written down in notes during the study.

4.5 Results

4.5.1 Reliability of the Animated Scales

To assess the psychological needs in SDT, we applied the PENS questionnaire to construct the perceived competence, relatedness, and autonomy, and IMI to measure the enjoyment level. We changed the scale from a bipolar scale to a unipolar scale to improve the granularity of the responses, based on results from previous studies showing that 7-8-year-old children had difficulty in understanding bipolar scales.

The modified scale showed good reliability for the perceived autonomy (Cronbach's alpha of 0.85 for the touch-screen interface and 0.77 for the tangible interface group) and enjoyment level (Cronbach's alpha of 0.65 and 0.68 respectively) constructs. However, the Cronbach's alpha for the perceived competence was relatively poor, with 0.39 for the screen-touch group and 0.42 for the tangible group. In our study, we found that some children were confused to answer the questions assessing their perceived relatedness and said that there was no "other player". Thus, we did not analyze the results for perceived relatedness here.

4.5.2 Effects of Different Interaction Types

Our first research question investigates the different effects between the two different interaction types on the learning experience. For each dependent measure of perceived competence, perceived autonomy, and feelings of enjoyment we used the repeated measures ANOVA, analyzing the within-subjects factor of different interactions (screen-touch vs. tangible). We found no significant effect of condition on the values of perceived competence, perceived autonomy, and feelings of enjoyment in relation to the two different interaction types (see Table 4.2).

Table 4.2 The average values under different interaction types.

	Competence M(SD)	**Autonomy M(SD)**	**Enjoyment M(SD)**
Screen-touch	5.44(0.97)	5.00(1.43)	5.78(1.24)
Tangible	5.42(1.03)	5.16(1.35)	5.89(1.27)

4.5.3 Effects of Feedback Mechanics

Our second research question investigates the differences between the two feedback mechanics. To investigate this question, we performed a repeated measures ANOVA, with interaction type as a within-subject factor and feedback mechanism as a between-subject factor. Table 4.3 shows the average values for perceived competence, perceived autonomy, and enjoyment level in relation to different feedback mechanics.

Figure 4.13 illustrates the significant effects of different feedback mechanics on perceived competence ($F(1,30) = 4.85$, $p = 0.036$, partial $\eta 2 = 0.14$), perceived autonomy ($F(1,30) = 5.05$, $p = 0.032$, partial $\eta 2 = 0.14$), and enjoyment level ($F(1,30) = 4.86$, $p = 0.035$, partial $\eta 2 = 0.14$).

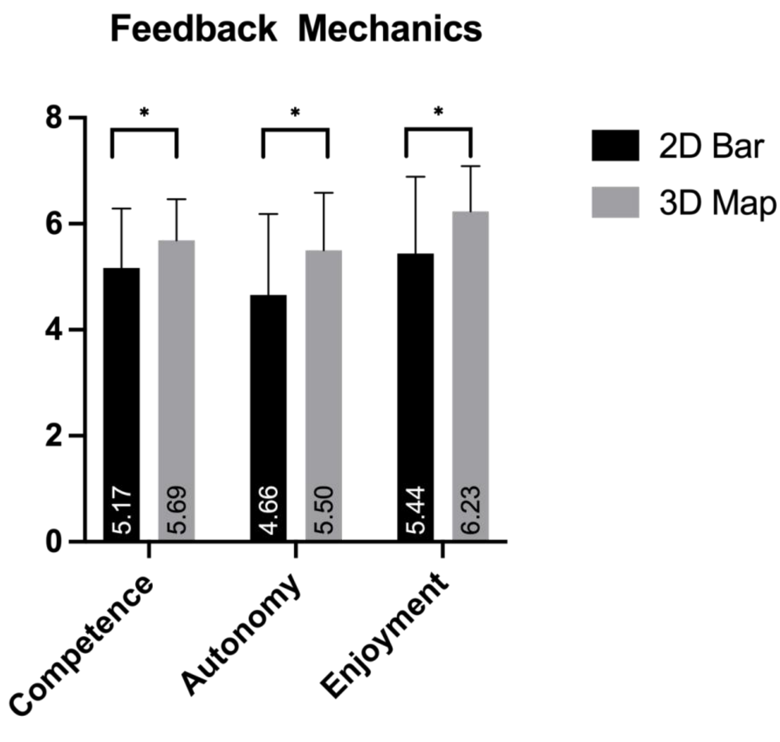

Figure 4.13 The comparison between different feedback mechanics.

Table 4.3 The average values under different feedback mechanics.

	Competence M(SD)	Autonomy M(SD)	Enjoyment M(SD)
2D Progress Bar	5.17(0.88)	4.66(1.18)	5.44(1.21)
3D Map	5.70(0.34)	5.50(0.93)	6.23(0.80)

4.5.4 Interaction Effects

Analysis of the full models showed that feedback mechanics yielded no significant interaction effect with interaction types on perceived competence ($F(1,30) = 0.33$, $p = 0.570$), perceived autonomy ($F(1,30) = 2.82$, $p = 0.100$), or enjoyment level ($F(1,30) = 0.58$, $p = 0.450$).

Although there was no significant interaction effect, we noticed that the screen-touch interaction with diegetic feedback triggered the highest competence, autonomy, and enjoyment level among the four conditions. While the tangible interaction with non-diegetic feedback perceived the lowest competence, autonomy, and enjoyment (see Table 4.4). This could be caused by children feeling satisfied receiving feedback from the 2D progress bar after taking some actions without spending too much time or effort on it. While they would expect richer feedback as rewards if they put more effort into the activities, otherwise they would be unsatisfied, leading to a decreased motivation.

Table 4.4 The average values under four different conditions.

	Competence M(SD)	Autonomy M(SD)	Enjoyment M(SD)
Screen-touch with progress bar	5.25(1.15)	4.81(1.72)	5.47(1.45)
Screen-touch with progress map	5.63(0.76)	5.19(1.10)	6.09(0.92)
Tangible with progress bar	5.08(1.13)	4.50(1.35)	5.41(1.50)
Tangible with progress map	5.75(0.81)	5.81(1.00)	5.89(1.27)

4.5.5 Qualitative Results

We also conducted interviews with the children at the end of the study, aiming to derive more meaningful insights for future game design.

Which version do you prefer?

After playing both the screen-touch and tangible versions of the game, children were asked about their preferences between the two versions. We found that children had different preferences on the two different interaction styles. 7 children preferred the screen-touch version, 17 said they liked the tangible interaction more, and 8 said they found no difference between them.

Why do you like the screen-touch interaction?

We tried to find out the reasons behind children's preferences. Children were asked to express why they preferred certain versions. Children who preferred the screen-touch version mainly indicated that this version was easy to play (e.g., "it's much easier and faster", participant 1), comparing to the tangible interaction which was more difficult and required more effort (e.g., "it's too difficult to control", participant 4). On the other hand, children who said that they liked the tangible interaction version more and experienced more fun during play, especially after they fully understood how the game worked (e.g., "because it's so interesting", participant 3; "when I figured out how it really works it's really fun to play", participant 7). Some children preferred the tangible interaction due to the screen-touch version being considered as "boring" compared to the tangible version (e.g., "the other one is boring", participant 11).

What else do you want to have in the game?

At the end of the interview, children were asked for improvement suggestions for the two games in general. The size of the virtual objects was the most frequently mentioned factor (e.g., "the animal is too small, I can't see it sometimes", participant 11; "you can make the paper larger, so I can make the animal walk from here to there", participant 3). The speed of the animal moving is another factor mentioned by children (e.g., "animals run too slowly", participant 12; "animals should run faster", participant 19). One child also mentioned that "people" could walk on the progress map ("there should be some people walking on the map, you see there are roads, they can walk on the roads", participant 21).

Parents' Perspective

We did not intend to interview the parents in the study. However, some parents also expressed their opinions spontaneously. Parents saw the effectiveness in the tangible interaction regarding "concentrating on activities" ("when kids are reading books or doing homework, they always make some small actions, such as shaking their legs, and they are easily distracted. But when playing this game, they have to use both their hands and focus on it, I think it's more helpful for concentrating", parent 1). Another parent thought the game was more useful in helping children remember things than a traditional approach ("you can put the knowledge they need to remember in the game, such as the multiplication table. When children engage with the game, they will remember this knowledge during play. It's easier for them to remember things than only using books", parent 2).

Observation

While playing with the tangible interaction version, we noticed that children were able to make meaningful real-world analogue actions by controlling the virtual content with the paper and understand the direct responses corresponding to their actions. They understood that by lifting the paper, the animal would start to move. They lifted the paper to let the animal run faster and stopped it by lifting it in another direction. Besides, they were also able to understand that they had to turn the book to make the animal face in the desired direction. However, we observed that children could not carry out the actions in a nuanced way. They were not sure to what extent they should lift the paper. Some children lifted the paper extremely and lost track of the marker several times, asking, "where is the animal? I can't see it anymore", (participant 4). Some would move the animal in opposite directions or move the book too much, resulting in moving the animals several circles around the food with extra effort or missing the animal out of the screen area.

4.6 Discussion and Limitations

4.6.1 Discussion

Applying Tangible Interaction in AR Games

Overall, our results indicated no significant difference between the two examined interaction types (screen-touch vs. tangible) in terms of perceived competence, perceived autonomy, and enjoyment level. For serious AR games, a simple screen-touch interaction ostensibly suffices.

However, the interviews showed differentiated reasons for possibly liking one over the other. Screen-touch interaction required less effort from children but could make some of them feel bored. While the tangible interaction has the potential to motivate children as they found it interesting and fun even though it required more effort. However, when children perceived the interaction as too difficult, their motivation might decrease. In line with Flow Theory (Csikszentmihalyi, 1997; Nakamura and Csikszentmihalyi, 2009), people are more engaged with an activity when their skills match with the challenges. High skill, low challenge would lead to boredom, whereas low skill, high challenge would lead to anxiety (Csikszentmihalyi, 1997; Nakamura and Csikszentmihalyi, 2009). A similar result may have manifested itself here, leveling out the motivating qualities and ultimately leading to no measurable effect. Besides, the results also correspond to previous implications on the usability of AR interactions that children will not choose to use an educational application simply because it is easy to use, but they might be engaged in the game especially because the interactions are challenging in the game (Radu, 2016). Players should perceive challenges that enhance their skills and receive immediate feedback about their actions to have a more immersive experience (Ariza, Sánchez-Ruiz, & González-Calero, 2019).

Moreover, the tangible interaction required children to practice in order to grasp the precise and somewhat cumbersome controls of this interface. However, they were not demotivated in using it. Instead, we observed that children enjoyed exploring and practicing the controls of the tangible interface and laughed when they made mistakes such as making the animal walk in circles or out of the paper. This suggests that the tangible interaction has the potential to facilitate children's development of fine motor skills such as hand-eye coordination and spatial abilities, as identified by Radu and MacIntyre (2012), without demotivating them.

Therefore, we do still see the potential in applying this tangible interaction implementation for designing other games to provide motivating and immersive AR experiences for children. Traditional tangible interaction tools, such as cubes or paddles, might confuse children in understanding how their actions make the system react and children often expect more physical-analogue interactions (Hornecker and Dünser, 2007). The proposed tangible interaction in this paper of using the textbook to control the game could be applied as an alternative solution with which children can make meaningful actions and understand the direct response towards their actions.

It should be noted that the current game is based on handheld devices due to the experiment and technology limitations. The screen is relatively small, which might influence the overall experience. It might be more effective working with wearable devices such as glasses where children can experience more natural and intuitive interactions between the virtual and real objects.

In terms of its educational purpose, this game can be easily inserted into different textbooks at a low cost and be extended to different game concepts, engaging children to interact with educational textbooks more and motivating them to do exercises.

When designing successful digital games for children, it is important for the game to be easy to learn but hard to master (Bekker *et al.*, 2005). Designers should provide the right degree of difficulty levels in the AR interactions to keep children motivated (Radu, 2016). Hence, more considerations should be taken on how to design the tangible interaction effectively. For example, to what extent should children turn or tilt the physical interface to make the virtual objects react without tracking loss? How to design the border on the physical interface restricting where the virtual animals can walk onto to minimize the chance of losing the animals without limiting the space for children to explore in the game?

Leveraging Diegetic Feedback of AR to Increase Learners' Motivation

Overall, our data indicated that the diegetic feedback (progress map) was significantly preferable over the non-diegetic feedback (progress bar). When receiving feedback through the progress map, children significantly perceived more competence and autonomy, and they reported significantly stronger feelings of enjoyment. With the progress bar, children might perceive the feedback as controlling and see the activity more like a task they have to finish rather than a game they want to play with. Or vice versa, the setting of filling up a natural pasture with animals could be felt as more self-determined than following the game rules to completion.

This result is in line with SDT: intrinsic motivation does not increase solely due to higher feelings of competence unless it is also accompanied by an increased feeling of autonomy (Ryan and Deci, 2000b). Even positive feedback may impede people's inherent need for autonomy and thus decrease their intrinsic motivation (Deci, Koestner, & Ryan, 1999).

Moreover, when designing for motivating and immersive experience for children, we suggest designers to utilize the special affordance of AR to create immersive stories and play spaces. For example, they can integrate the virtual game elements more in a spatial setting and combine them with the real world to generate diegetic mixed reality elements, and subsequently gamify the learning environment.

4.6.2 Limitations of the Study

This study has some limitations. Firstly, we applied a new scale modified from existing validated scales to avoid the risk of collecting extreme positive results from children as found in other studies. The reliability analysis showed that participants might have a different understanding of sub-questions measuring perceived competence. Therefore, the results pertaining to the competence scale should be considered with caution. Although we also conducted a small pilot study and analyzed the questionnaire results together with the results from the qualitative data, a larger scale study should be carried out to validate the modified scales in the future.

Secondly, we did not measure the learning performance of the participants in the game since the exercises we used were simple calculations and learning gains would be minimal. In our previous study, we measured the correctness rate between doing exercises on AR game and on paper exercises and found no significant difference. However, it would be interesting to include new knowledge and concepts to children and let them do the exercises to examine the effectiveness on the learning outcomes with different versions of the game.

Besides, we did not collect additional information from the participants, such as their current maths ability and attitudes towards it. Differences might exist among the participants especially because they came from different schools in the Netherlands, which might influence the motivational effect as well. In the discussion we hypothesized that the two interaction types might have had an effect on the difficulty of the game; however this remains untested. Similarly, we designed the feedback part of the experiment to contrast non-diegetic and non-AR specific feedback with diegetic and more AR-specific feedback. This was done to gauge whether an AR enabled-paradigm can improve motivation. Although we contend that a progress bar is typical for many serious games, the difference between the two conditions is arguably big and consists of more than one variable. Now that we found a significant positive effect of using an AR-based progress map on motivation, further systematic research is necessary to delineate whether this is due to its diegetic character, the AR implementation, the visual pleasantness, or something else.

4.7 Conclusion

As a part of the research, this study investigated how to incorporate competence-supportive elements in AR serious games to enhance children's learning experience. To be more specific, in our game, we challenged children with two different types of interactions. Children interacted with the 3D animals in the game either with tangible interaction by turning and lifting their physical textbooks or with screen-touch interaction by pointing on the screen, in order to find out the maths exercises. We provided children with different types of feedback as the closure of the task. Children received immediate feedback after finishing the exercise either by a 2D progress bar or by a 3D progress map. With the 3D progress map, if the exercise was answered correctly, children could see the animals appear on an extra map. The 2D progress bar was analogous to how they were used in traditional digital games.

We conducted experiments with 7-8 years old children and figured out how they reacted to these two different interaction styles as well as two different feedback mechanics when performing maths exercises in an AR game. The results of this study showed that there was a significant effect of feedback mechanics on motivation while playing the game, where children liked collecting animals and seeing how they populated a mixed reality map, over a simpler progress bar. There was no significant effect of screen-touch or tangible interaction on motivation, and no significant interaction effect between the feedback and interaction types. Recommendations were identified for designers to develop motivating serious AR games for children in terms of applying tangible interaction in AR games and leveraging diegetic feedback of AR to increase learning motivation.

In the next chapter, the current prototype will be iterated upon, integrating other game design paradigms such as social connectedness inspired by the relatedness within SDT.

CHAPTER

FIVE

DESIGN AND EVALUATION OF A RELATEDNESS-SUPPORTIVE AR SERIOUS GAME

Chapter 5: Design and Evaluation of a Relatedness-Supportive AR Serious Game[16]

5.1 Introduction

In the previous chapter, we created a game inspired by designing around the feeling of competence, including challenge and completion. We found that in the context of AR serious games, the 3D progress map with animations stimulated children's motivation the most. We also identified the potential for applying tangible interactions in AR settings although there was no significant improvement on motivation.

In this chapter we focused on designing around the concept of relatedness. We explored the engaging potential of social AR games with a special focus on the way competition and fellowship impacted the shared augmented play space and came up with design guidelines to support the development of social AR serious games and new forms of social play in a shared-world AR system. We designed and developed a book-based AR social learning game for elementary school children, aiming at improving children's learning experience while practicing mathematics by interacting with each other and engaging with the learning materials in a more fun way. In the end, we also introduced the design of another possible collaborative mathematics learning game called MathBuilder.

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[16] **Based on:**

Jingya Li, Erik D. van der Spek, Xiaoyu Yu, Jun Hu, and Loe Feijs. (2020). Exploring an augmented reality social learning game for elementary school students. In *Proceedings of the Interaction Design and Children Conference* (pp. 508-518).

van der Stappen, A., Liu, Y., Xu, J., Yu, X., Li, J., & Van Der Spek, E. D. (2019, October). MathBuilder: A collaborative AR maths game for elementary school students. In *Extended Abstracts of the Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts* (pp. 731-738)

5.2 Related Work

In Chapter 2, we explained our theoretical framework as we mapped the fellowship and the competition in PLEX to the relatedness within SDT. In this section, we first reviewed the effects of different social elements on children in existing serious games, and then studied how different social elements were applied in AR serious games.

5.2.1 Effects of Social Elements in Serious Games

As mentioned before, a higher level of maths performance at the beginning of the elementary school years might predict an increased motivation towards mathematics, which would further predict a high level of maths performance in the later elementary school years, suggesting that the motivation and positive attitudes towards maths are important in the learning environment for children (Bergin, 2016). Social interactions have been proved to generate positive effects in the educational context to improve the learning experience (Freitas and Campos, 2008).

Consequently, an argument arose that collaborative learning in serious games could support learners in articulating the knowledge (van der Meij, Albers, & Leemkuil, 2011). However, according to Wouters *et al.* (2013), previous work on comparing collaborative and solitary game play is ambiguous. Some studies resulted in higher motivational effects and learning outcomes with collaborative activities and some did not.

Besides collaboration, competition is also a frequently used social element to engage and motivate students in serious games (Wouters *et al.*, 2013; Plass *et al.*, 2013). However, previous studies revealed different findings on the impact of these two social elements on learning experience. Plass *et al.* (2013) provided empirical evidence based on an evaluation of a digital game to develop arithmetic fluency. They studied and examined the different impacts of both collaborative and competitive modes on situational interest and emphasized that a competitive game mode was more effective than a collaborative or individual mode in developing arithmetic skills and increasing situational interest and enjoyment for students. Pareto *et al.* (2012) presented a digital mathematics game and found that both collaboration and competition modes generated a significant motivational effect on students. Siu (2014) examined the effects of collaboration and competition on children's learning experience and found out that in general, the competition game might lead to a more enjoyable experience. According to the study, competition and collaboration might be perceived differently by different types of players based on their personal conditions. Consequently, the study suggested serious game designers apply different mechanics for different players.

Not only is more research needed to deliver effective design guidelines for collaborative and competitive activities in learning games, but also research on how children in the early elementary school age would behave in these two social contexts. Besides, although collaboration and competition modes have been widely applied in serious games, the augmented physical play space generated between two players of an AR serious game may create a notably different social setting than in traditional digital games. Therefore, it is necessary to take a specific look at the social elements in the AR environment.

5.2.2 Social Elements Applied in AR Serious Games

AR technology allows users to interact with virtual environments on top of the physical objects and engage in natural communication in the real world, offering unique benefits that are unachievable with the use of other forms of technologies (Klopfer, 2008; Li *et al.*, 2011; Phon, Ali, & Abd Halim, 2014; Radu and Schneider, 2019). One of the unique benefits of AR is its capacity to support social interactions since users can see the same content in the same space in real time (Bühling *et al.*, 2012).

In the educational domain, the collaborative feature in AR has the potential to be a facilitator to learning, allowing students to engage with their classmates and direct each other to learn different aspects of the learning content (Bujak *et al.*, 2013). Billinghurst, Kato, & Poupyrev (2008) presented the potential of collaboration with tangible AR interfaces. In their study, a variety of AR tangible interfaces were tested that could enhance and support natural face-to-face collaboration and interaction in the real-world environment among multiple users through a headset. Cascales-Martínez *et al.* (2016) applied a collaborative AR-enhanced tabletop system to promote maths learning with students aged 6-12 with special needs. Their results revealed that the AR tabletop improved children's learning motivation and significantly increased their knowledge acquisition. According to their study, the AR system offered opportunities for children to collaborate in solving problems and establishing information feedback among them. Chen and Wang (2015) employed AR in the science learning process and enabled face-to-face interactions among children in the classroom. They found that their AR system led to a positive effect on learning achievement and children were in favor of learning with AR. Chiang, Yang, & Hwang (2014) designed a location-based AR environment to guide children to share knowledge in an inquiry learning experience and found that children were more engaged with the AR learning activity than the conventional mobile learning experience. In this study, children were all able to express their viewpoints during the discussion process freely. According to the researchers, this process enabled children to ask questions actively and think cooperatively. Children who knew the correct answers would share their knowledge with their classmates. Schrier (2006) designed and developed a location-based AR game called Reliving the Revolution to teach 21st Century skills such as communication and collaboration by applying collaborative AR features. Alien Contact! is an AR game that could engage children in a collaborative participatory learning activity, which aimed at enhancing their learning experience in subjects such as math, language, arts, and scientific literacy (Dunleavy, Dede, & Mitchell, 2009; O'Shea et al., 2009). Besides, the elementary school maths classroom is an ideal place to apply AR, which enables children to learn difficult maths concepts more easily and in a more engaging way than traditional approaches (Dünser, Grasset, & Billinghurst, 2008). Radu, MacIntyre, & Lourenco (2016) conducted evaluations on multiple AR prototypes for maths classrooms based on paper and mobile applications with elementary school teachers and acknowledged the potential of using AR prototypes in a maths classroom. Other researchers also suggested that additional interactive strategies such as role-play could be integrated into the AR applications to improve the experience and social interactions among users (Bujak *et al.*, 2013).

Several games integrated both competitive and collaborative features where players have to work together in teams while competing against other groups without differentiating the effects of the two social elements (Laine, 2018). For example, social elements were included in an AR game about immune-defence for science education where students had to work in groups to defend other groups' attack (Nielsen, Brandt, & Swensen, 2016). In the study of an AR game for arithmetic learning for first-grade students to third-grade students in an elementary school (Young, Kristanda, & Hansun, 2016), a leaderboard scene was applied to show the players with the highest score including player names, score, and time of each player. The results showed that competition was the most effective factor that influences players learning motivation. Students were motivated to play the game with the intention to get better score than their classmates (Young, Kristanda, & Hansun, 2016). In the study of an AR game for science learning designed by Costa *et al.* (2018), students aged 8 to 12 played the game in groups to finish the challenges together and they could find out which group was the first place and won the prize in the end. In another study, students from different groups competed with each other by answering questions with an AR game for high school Chemistry learning (Hsiao and Rashvand, 2011). The results indicated that students showed stronger preferences towards the AR learning environments in the subscales of collaboration and competition. Wijers, Jonker, & Drijvers (2010) evaluated an AR maths learning game called MobileMath, mentioning competition as an essential factor in enhancing students' engagement with the game. In this game, competition was implemented in terms of teams of students playing against each other (Schmitz, Klemke, & Specht, 2012). Cheng *et al.* (2019) designed an AR game called MathMon, where sixth-grade students aged 11 and 12 were teamed up to look for hidden maths monsters on campus. Students needed to work together to solve a series of prime factor problems in order to catch the maths monsters. According to the authors, they also included a competition element in the game, in which students competed to be the first team to find all the monsters to further engage the students and develop their problem-solving skills with a pop-up leaderboard to show the progress and scores of each group (Cheng *et al.*, 2019).

However, despite that some of the studies mentioned above have successfully shown the potential of social AR learning games to enhance engagement or improve learning outcomes over traditional digital serious games, most of them only allowed one student to control the AR experience and let the rest of the group observe (Bujaka *et al.*, 2013), or were designed as mostly single-player experiences with asynchronous interactions (Bhattacharyya *et al.*, 2019). There have not been many AR learning systems designed specifically for multiplayer collaborations (Bühling *et al.*, 2012). Some AR games were played individually but had competitive elements in them, such as comparing game points or achievements with other players (e.g., Bühling *et al.*, 2012; Hwang *et al.*, 2016; Pombo *et al.*, 2017; Young, Kristanda, & Hansun, 2016).

To conclude, AR games that offer players a shared and real-time AR environment as well as social interactions with each other, remain unexplored at present (Bhattacharyya *et al.*, 2019). A large number of currently available AR systems still only offer limited opportunities for multiplayer experience (Bhattacharyya *et al.*, 2019). A single-player AR game is the most common game mode in which players experience the game alone without interacting with other players (Laine, 2018). Besides, previous work did not focus on how players perceived their relationship with each other and the way they played the games under different social conditions in the AR settings specifically.

The design guidelines for shared-world AR systems do not even exist (Bhattacharyya *et al.*, 2019), let alone the design guidelines for AR serious games. The empirically validated design guidelines for AR social learning games remain unexplored. It is still unclear how to combine social elements in AR serious games to engage students in the learning activities. With the increasing interest in applying social elements in AR learning games, there is an urgent need to investigate how to amplify the advantages of social interactions in AR serious games to enhance learning motivation and experience. Therefore, in our research, we explored how students would behave under different social contexts and the possible changes in children's perceptions from different perspectives.

5.2.3 Research Questions

In this chapter we applied the relatedness in SDT to understand how different social modes in AR serious games influence children's learning experiences. Within SDT, relatedness refers to the feelings of social connectedness with others (Ryan and Deci, 2000b). We designed two different types of social interactions in the AR game, which were fellowship and competition. We aimed to answer the second research question of this thesis:

RQ2. How to amplify the advantages of social interactions in AR serious games based on notions of perceived relatedness in Self-determination theory to enhance children's learning motivation and experience?

- **2.1** Which types of social interactions in terms of competition and fellowship should we integrate into AR serious games for children?
- **2.2** How do children perceive their social interactions in terms of competition and fellowship in AR serious games?

5.3 Design Process

In this section, we explain the methods used in our research process, including the participatory design sessions and how the outcomes of previous studies affect our design decisions, and the new game concepts of See Me Roar with relatedness-supportive features.

5.3.1 Participatory Design Sessions

To find inspirations for the concepts of the relatedness-supportive AR serious game, we first conducted participatory design sessions with eight participants (three elementary school students, one high school student, and four university students). See Figure 5.1. We first provided the background information and design challenges to participants that we were going to design an AR game to make maths exercises more fun for elementary school children. In the previous participatory design sessions we conducted with elementary school children (Li *et al.*, 2017), we came up with the idea of 3D animals running on top of the physical books and found out that children enjoyed playing with these 3D animals in the AR world. Restarting from the idea of 3D animals again, in this study, we asked participants to come up with a maths game scenario in the context of an animal world through a low-tech prototyping method (Sluis-Thiescheffer, Bekker, & Eggen, 2007) and give presentations about their design concepts to other participants in the same participatory design session. Then participants were asked to iterate their design ideas into a multiplayer mode and explain their new concepts to others. Each participatory design session took around 1 hour.

Figure 5.1 Two participatory design sessions.

Participants developed and extended their ideas based on the animal concepts. We analyzed the results of the low-tech prototypes (see Figure 5.2) and the presentations from the participants using the Thematic Analysis method (Lazar, Feng, & Hochheiser, 2017). All participants mentioned using animals to represent themselves in the game world. One group developed a game concept of the food chain in the animal kingdom, which involves different levels of animals, where each animal eats different types of food: e.g., the leopard eats the rabbit, and the rabbit eats grass (Figure 5.2).

Figure 5.2 Results of the participatory design sessions, first line from left to right: monkeys live on the tree; elephants walk in the forest; the leopard eats the rabbit, and the rabbit eats grass; second line from left to right: one player can change the numbers in an equation and the other can change the operators for each other.

Participants also put animals in different environments related to the real-world environment (e.g., monkeys live on the tree, elephants walk in the forest). According to the participants, this game concept could also add additional value to the learning experience, where students can also acquire knowledge about the animal itself as well (e.g., eating habits of certain animals).

When asked to design the game into multiplayer mode, competition and collaboration were the first ideas that participants came up with. Developed concepts included students being able to compare who is faster to eat the food in the game or having collaborative features with tasks division, where each player has different responsibilities in the game. For example, one player can change the numbers in an equation, and the other can change the operators for each other to make the game more flexible. Participants also mentioned that face-to-face discussion in a team could be helpful for children in maths learning because it might be necessary for them to have the opportunity to ask questions and get explanations without feeling shy.

Participants applied basic arithmetic exercises as the main content regarding the maths topics, including addition, subtraction, multiplication, division, and mixed calculations.

5.3.2 Game Concepts

Based on our theoretical framework, the results from our previous studies, and the current participatory design sessions, we designed and developed our relatedness-supportive AR serious game. The newly developed game can be played in groups of two. Children use the mobile device to scan the physical book page and look for virtual 3D objects, such as animals, plants, and food. The virtual animals will ask several mathematics questions related to the content on the book page, and the goal is to guide the animal to eat the plant or food that has the correct answer next to it by looking around the book page with the AR camera. See Figure 5.3. The AR game was developed in Unity 3D with Vuforia SDK.

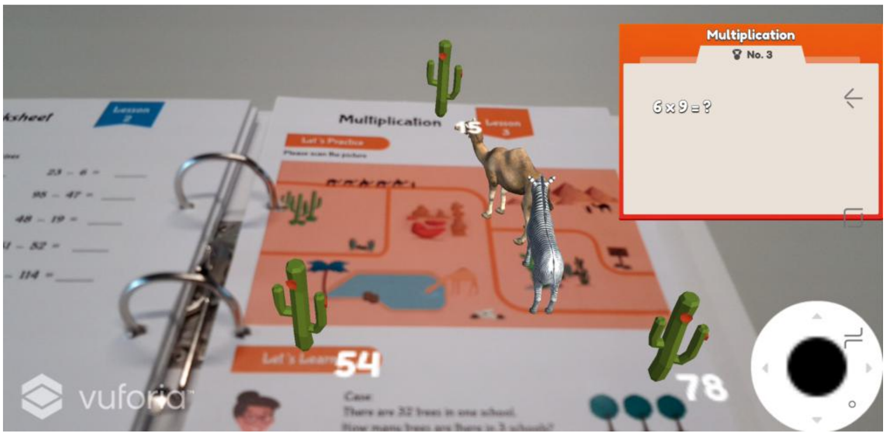


Figure 5.3 Design of the AR game prototype. Finding virtual objects standing on top of the physical textbooks through AR camera.

In See Me Roar, we designed the social connections among children into two modes, collaboration and competition, to produce the feeling of relatedness for several reasons. Firstly, according to SDT, the feeling of relatedness concerns the sense of belonging (Deci, Koestner, & Ryan, 1999; Ryan and Deci, 2000b), which could be affected by teammates in the real world and in the digital game (Groh, 2012; Rigby and Ryan, 2011). In Chapter 2, we mapped competition and fellowship to relatedness based on SDT and PLEX. Competition refers to the experience of competing against each other, and fellowship refers to the experience of doing something as a group, like collaboration. Secondly, based on the related work in Section 5.2, these two modes are the most frequently applied social elements in serious games and AR experiences. In addition, in the participatory design sessions described in Section 5.3.1, participants have also developed the game concepts into collaboration and competition modes. Therefore, we were curious to find out how children would perceive these two social interaction modes, and which of these two social interactions we should integrate in AR serious games. Below we describe the detailed game mechanism of these two modes.

Competition Mode

In the PLEX framework, competition is defined as contest with oneself or an opponent. In our game, children see the same tasks and need to finish the tasks as fast as possible before the other one does to win the game. Children can see other's animal on top of their textbook, and they have to compete with each other on who can get the correct answer first. To be more specific, in the competition mode, children first choose an animal to represent themselves in the game world (the idea we collected in Section 5.3.1) and then join the competition with each other. When they are ready, they will receive the same maths exercise and can use their own mobile devices to scan and look around the textbook page to find several virtual answers. Only one of them is the correct answer. The goal is to get the correct answer before the other one does. The one who eats the correct answer faster wins the game, and the winning animal will play a cheerful animation.

Collaboration Mode

In the PLEX framework, fellowship is described as friendship, communality or intimacy. In our game, we offer children the opportunity to cooperate with each other, and we call it the collaboration mode. In the collaboration mode, the game settings are the same as in the competition mode, except that two children receive asymmetric information through their own mobile devices. They are assigned different tasks in the game and need to collaborate with each other to finish the game. One of them only sees the exercises, and the other one sees the answers and needs to control the animals to find out the correct answer. They need to communicate with each other to finish the game. Children take turns to see the exercises and the answers in the game.

5.3.3 Textbook Design

AR can combine the benefits of physical learning materials with new interaction opportunities, making it easier to integrate games with traditional instructional materials such as textbooks (Bujak *et al.*, 2013; Dünser, Grasset, & Billinghurst, 2008; Li *et al.*, 2017). Therefore, in this study, we applied the textbook as the augmented play space for learning.

In our previous study (Chapter 4), we found that elementary school children might have difficulties in scanning the image marker for AR content sometimes, which might influence their overall experience negatively. Therefore, we made the AR marker easier to scan to avoid frustration. We re-designed the maths textbook based on a standard Dutch elementary maths textbook of group 5. The structure of the maths textbook contains three different parts, viz. the AR map, the knowledge explanation, and the exercises. See Figure 5.4.

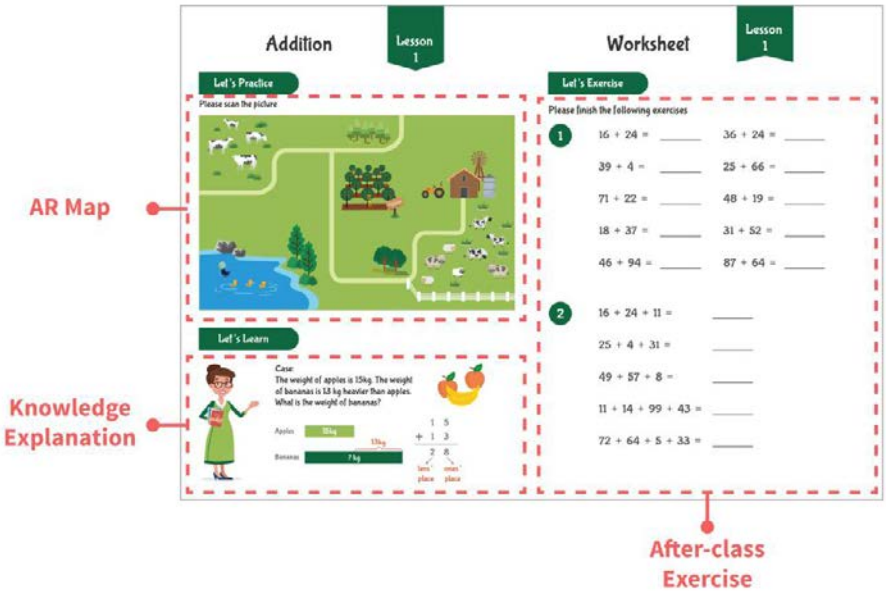


Figure 5.4 Structure of the AR mathematics textbook: the AR map, the knowledge explanation, and the after-class exercise.

The exercises were chosen from the maths textbook we used in Chapter 3. With the AR maths textbook, children can first learn from the knowledge explanation part and then practice with the related exercises in the following page. The AR textbook contains four different themes (farm, ocean, desert, and forest) with different maths content (addition, subtraction, multiplication, and division) based on the insights collected from the participatory design sessions. See Figure 5.5.

Figure 5.5 Four themes on the AR mathematics textbook: farm theme with additional learning and exercises; ocean theme with subtraction learning and exercises; desert theme with multiplication learning and exercises; forest theme with division learning and exercises.

5.4 User Study

To explore children's different perceptions towards different social interactions in AR serious games, we first did a pilot study (Section 5.4.1-5.4.3), then a large formal study (Section 5.4.4). Sections 5.5 and 5.6 address the results, discussion, and limitations of that formal study. It should be noted that we were not only aiming to draw a conclusion from the study that whether collaboration or competition was better for AR serious games. In fact, we would also like to explore the new forms in social AR serious games and inspire other design decisions by better understanding children's perceptions towards these two types of social interactions.

5.4.1 Pilot Study

We conducted a pilot study with four elementary school children aged 8-12 to collect preliminary results to guide further study and see if they could understand the current AR game. The study was carried out at children's homes in the Netherlands.

We first explained the game to the participants, and then they started with the competition mode. After the participants finished all the exercises in the competition mode, they were asked to rate their relationship with the other player in the group by using the Inclusion of Community in Self Scale (Mashek, Cannaday, Tangney, 2007) (IoCiS), which is meant to evaluate how individuals perceive their relationships with others scored from 1 to 7 (see Figure 5.6). Then we conducted interviews with participants based on their ratings in the scale. We also observed and took notes on their behaviors and recorded their verbal conversations during the game. After the first round of interviews, participants continued to experience the collaboration mode. The IoCiS scale and semi-structured interviews were conducted with the participants in the same way.

Figure 5.6 Inclusion of Community in Self Scale adapted from Mashek, Cannaday, Tangney (2007).

5.4.2 Results of the Pilot Study

For group 1, in the competition mode, we noticed that participant A (boy, 8 years old) was more active, and had more positive behaviors compared to participant B (girl, 8 years old), while B remained quiet for most of the time and had few verbal expressions. Once A finished the exercise, he would turn to B and asked B if she had any problem or question. During the game, they did not communicate much but only smiled at each other once in the beginning and only talked about the game elements when A saw two elephants in the game and checked with B if they had picked the same animal.

In the collaboration mode, more positive behaviors were noted, especially for B, who was more active, smiled more, and talked more during the game. A and B communicated more than in the collaboration mode since they had different responsibilities and had to give information to each other to finish the exercise.

For example, when B was the one who saw the exercise and A saw the answers, they discussed how to calculate the exercise since A did not find the answer B gave. They also discussed the animal characters several times during the game and checked with each other about which animal to choose.

For group 2, both participants behaved competitively in the competition mode; they checked with each other every time to make sure that they started at the same time. Participant C (girl, 12 years old) smiled and cheered after she won the game each time and would also look at participant D (girl, 9 years old)'s screen after finishing the game and showed off to her. At the same time, D asked to play alone several times without C because she wanted her animal to eat the correct answer as well.

C and D were both excited and happy after hearing about the rules for the collaborative mode. They communicated about which animals to choose, calculated the maths exercises together, and decided together where to move the animal. D showed more positive feelings after they got the correct answer and even cheered up with both arms several times. Figure 5.7 shows the participants in the pilot study.

Figure 5.7 Participants in the pilot study (left: participant A and B; right: participant C and D).

The results of the self-report IoCiS scale (where 7 is most related and 1 is least related) showed that all participants perceived higher relatedness with the collaboration mode (Mean = 6.50) than the competition mode (Mean = 4.25). We asked the participants for the reasons for the ratings. A and B said that they did not feel close to each other in the competition mode. A indicated that he would prefer to play the game alone, and B felt that they did not talk too much in the game. When asked about the reasons for giving a higher score to the collaboration mode, A thought that the teamwork to finish the game made them closer to each other, and B attributed this difference to how many conversations they had during the game. C and D felt that although the competition mode could somewhat enhance their intimacy, they were still separated and not bonded together. On the other hand, they felt that they were more closely united in the collaboration mode because they worked together.

Each participant was asked which version of the game they preferred. Three of them preferred the collaboration mode for different reasons, mentioning that taking turns could bring a different experience (B: “the fun part of the collaboration was that you could take turns”) and the feeling of being responsible in the teamwork, which made them feel more immersed and engaged in the game (C: “I like that kind of game, teamwork, that’s very fun for me”; D: “in collaboration, I felt like in a team so I could not take my team slow. collaboration made me feel more responsible, so I wanted to win more than the competition version. collaboration made me engage more, even though there was no winning or losing, I wanted to make the things right”). C also mentioned the factor of "win" or "lose" would affect how she experienced in the game (C: “if I have won more times, I would like it more”). Only A preferred the competition mode because he felt that it was more fun and he could win more times.

During the study, we noticed that participants looked at their partner’s screen several times. We asked them what they were looking at during the interview. According to them, they looked at the others’ screens in the competition mode because they wanted to know their progress so that they could win the game, while in the collaboration mode they wanted to check whether their calculation was correct or not. There was also a condition that the more skillful participants would like to help their partners in the game.

5.4.3 Insights of the Pilot Study

Overall, we found that participants had no difficulty in understanding the proposed AR game. They enjoyed playing with the game and even requested to play the game for more rounds spontaneously. Besides, they delivered natural conversations with each other during the game. However, the difference in the maths skills between the two players might have influenced their behaviors and interactions. Therefore, we are also interested to see the relations between children's own perception of their maths skills and their social behaviors in the game. In addition, we also noticed that participants had different focuses during the game play. For example, D focused on completing the exercises, while C focused on interacting with the animals. Therefore, we also investigated their play patterns directly by collecting their in-game behaviors with a screen recording software in the formal user study.

5.4.4 Formal Study

After the pilot study, we conducted the formal user study with 24 elementary students (Mean age = 9.04, SD = 1.04, 8 girls, 16 boys) in the city library in the Netherlands (see Figure 5.8). Participants were grouped in dyads based on having roughly the same age and were presented with the two modes of the game in a counterbalanced order. Participants in the same group knew one another well and communicated with each other regularly after school.

The procedure of the user study was similar to the pilot study. All participants were asked to fill in a questionnaire first, which addressed their self-rated (out of 10) maths skills. Then they were introduced to the rules of one of the modes and tried out the game for 2 minutes. Then participants started the game, receiving one exercise in each page (4 in total in each mode). After playing with one mode, we asked participants to rate their relationship with each other on the IoCiS scale and conducted interviews with them. Then they were asked to play the second mode with the same procedure. Each session with two participants took between 40 minutes and 1 hour.

Figure 5.8 Participants in the formal user study.

5.5 Results

5.5.1 Higher Perceived Relatedness in Collaboration Mode

A paired samples t-test found a significant effect of the type of multiplayer mode on the sense of Inclusion of Community in the Self ($t(23) = -4.23$, $p = 0.000$, Cohen's $d = 1.21$), where competition (Mean = 2.92, SD = 1.50) scored lower than collaboration (Mean = 5.08, SD = 2.02). From the results we can see that participants perceived more relatedness with the collaboration mode in the AR game.

We tried to find out the reasons behind this effect from the interviews. According to the participants, the AR collaboration mode offered them a shared space to work together as a team, where they could easily understand each other and help each other during the game. They perceived each other's presence in the real world more than in the virtual world (e.g., P7: "we had to work together, like a team"; P17: "I think it was easier for us because we shared what we saw"; P19: "it was fun to play with him. And he has helped me sometimes"; P20: "he was talking about something, and I could really understand what he was speaking. That's really good").

Regarding the competition mode, we noticed that although participants remained in the same face-to-face position as in the collaboration mode, they felt separated and did not pay much attention to the other player during the game (e.g., P2: "we didn't see each other quite often"; P3: "we didn't get together that much"; P5: "you could see each other in the game, but you didn't know what he was going to do"; P8: "didn't notice what the other one was doing"). Participants perceived each other's presence more in the virtual game world instead of in the real world (e.g., P13: "because my animal did not go too close to his animal"; P14: "we were not running too close in the game"; P20: "I could see him sometimes in the game, but I was in a team and he was in another team"). Participants also noticed that they talked less in the competition version and felt more competitive (e.g., P9: "we didn't really talk about that too much"; P11: "we were really fast in the game, I didn't talk with her much").

5.5.2 Higher Concentration in Competition Mode

During the competition mode, we noticed that participants seldom looked at each other's screen, we asked them if they had looked at the other's phones and the reasons behind this. Most participants said that they did not pay attention to the others next to them because they needed to concentrate on their own game (e.g., P4: "I was concentrated, and I wanted to win"). Some participants said that they looked at the other players' screen because they were curious and would like to check the progress of the other player when they had some problems (e.g., P2: "I was just looking to see if he was done or not, because I never found the other number"; P6: "I wanted to know how he played the game"; P14: "I just look because I wanted to know if she selected the same animal like me. And then I just stopped looking and concentrated on the game").

On the other hand, participants frequently looked at their partner's screen during the collaboration mode. According to these participants, they cared about how their partners would behave in the game as well as if they could find the correct answer (e.g., P8: "I was following her while she was playing to see if she was looking for the right answer"; P15: "because I also wanted to know if she did it right or not"). Some participants looked at the others' screen because they wanted to see the maths exercises and got the answers faster (e.g., P11: "I looked to see the question before she told me. So I already started calculating in my brain"; P19: "I just looked at the maths question so I could give the answer"; P20: "when we were in a team I was looking at what was the question and he was looking where was the answer for that").

5.5.3 Maths Skills and Time Spent

Participants rated their knowledge of maths relatively consistently, with a mean of 6.75 (SD = 1.482) and 87.5% of results falling between 5 and 8. One participate gave a score of 4, one 9, and one 10. The mode (the number that occurs most often) and median were both 7.

We calculated the total time participants spent on finding the right answer for each exercise, from the time they saw the exercise to the time they found the correct answer in collaboration and competition modes respectively. We found significant differences ($t(23) = -4.49$, $p = 0.000$, Cohen's $d = 0.88$) between the time spent on each exercise in the competition mode (Mean = 46.77 seconds, SD = 23.46) and in the collaboration mode (Mean = 64.83 seconds, SD = 17.27). On average, participants spent more time in the collaboration mode.

We found no significant correlation between the self-rated maths skills and the perceived relatedness, gender, and the time spent in the game in both modes of the AR game. This might be due to the consistent result of the maths skills.

5.5.4 Playing Patterns in the AR Social Serious Game

Differences between different players may lead to different playing styles and preferences (Yannakakis *et al.*, 2013). Although we did not find noteworthy relations between children's demographics and their behaviors during the gameplay, we were curious to explore how children behave in different game modes. We observed children's behaviors during the game and transcribed their conversations with the help of an external observer. We identified three playing patterns in each mode. However, the playing patterns of each child was changing during the game. It is not easy to identify the patterns for each of them. For example, one child started with walking around to try out the answers randomly in the game. Then, he noticed that the other child was focusing on the exercise, so he changed to calculate the exercise by himself too. The playing patterns are described below.

Competition Mode

In the competition mode, the first pattern was to calculate the exercise by themselves and try to get the correct answer as fast as possible. This type of players seldom talked to the others during the game. The second pattern was to follow the other player in the game. This type of players paid more attention to the other players. They asked the other player “where are you going?” during the game and yelled out when they saw their animals interacting with each other: “hey, your animal crashed on me!”. The third pattern was to try out the answers in the game randomly. We noticed that the players would direct the animal to eat any answer they saw in the game immediately and went for the next one if it was not the correct one.

Collaboration Mode

In the collaboration mode, we also identified three main communication patterns between the two players. The first pattern was to have a clear and separated role in the team. These participants would finish their own tasks they were assigned, either delivering the exercises or calculating for the answers. If they saw the exercises, they would just say “the question is…”. If they saw the answers, they would prefer to calculate by themselves and look for the answers without discussing them with their partners. The second pattern was to discuss and communicate a lot with the other player. They shared with each other what they were looking at and made decisions on one answer specifically: “I think the answer is…, what do you think?”. The last pattern was to give the answers directly. Although participants had to communicate with each other to finish the exercises, we noticed that some participants tended to give answers directly without discussing with their partners. After seeing the exercise, they would calculate by themselves and said to the other “the answer is…”.

Preference on the AR Features

We asked participants to pick the most interesting part of the game in general. The results showed that the combination of the virtual content and the physical book AR offered was the most appreciated feature for them. Participant highly enjoyed playing the game with the physical book (e.g., P2: “my favorite part was exploring the game on the book"; P3: "I like that you can really move the animals around the book"; P7: "I really like that with the book, because it is really funny that you don't see the animal like that (2D), and with the phone you see 3D animals. I like it really well"; P8: "I like to see the landscape (on the book), it is funny to see the animals in the phone").

Participants also thought that further exploration in the game world would be an interesting idea. For example, they would like to look around to find out some hidden answers floating all over the room. (e.g., P15: "instead of having the animals, yourself should be inside the game, like you are actually there. To play with others, you can also talk to the people, and then they would reply to you").

5.6 Discussion and Limitations

Our study examined how children perceived their relationships with each other in a social AR serious game and how they interacted with each other under different social contexts: competition and collaboration. To that end, we conducted an exploratory study where children could compete in the game or work together with each other.

5.6.1 Interactions in the Competition Mode

In general, under the competition game, children were more focused and immersed in the game world. We noticed that children tended to concentrate on themselves and tried to be faster to finish the exercises but barely talked to the other player. They were curious about each other's animals in the game world instead of the partner and the objects in the real world. For example, one participant said that the other player's animal "crashed" on her animal in the virtual game world.

The results of the perceived relatedness also showed that under competition mode, although children were presented with the same physical environment, they did not pay much attention to each other and had the feeling that they did not see each other. Participants felt separated and more competitive in the game, doing their own exercises with concentration and did not communicate with each other in the real world.

The three interaction patterns in the competition game also indicated that children mainly focused on the virtual world. Children were competitive and did not pay attention to the physical environment around them nor the physical textbook under the competition game. We observed little interaction with the physical environment in the competition game. Participants sometimes looked at each other's phones merely for the virtual animals but would stop looking once the game started.

5.6.2 Interactions in the Collaboration Mode

Regarding the collaboration mode, instead of being immersed in the game world, children tended to extend the boundaries of the game to the real world and to incorporate the other player more.

Our findings showed that children perceived higher relatedness in the collaboration mode. The interview results also showed that children perceived the teamwork and the presence of each other during the game play and communicated more in the real world. Children also felt close to their partners because they were helping each other during the game, and they could understand what they were talking about as a team. We also noticed that children would discuss together with each other under the collaboration game. They shared with each other what they were looking at and made decisions on one answer together.

The interactions with the physical objects in the real-world environment were also more obvious than in the competition version. During the game play, children would combine the virtual animals with the content in the maths textbook. For example, one participant noticed that there was a bridge in the image on one book page and said that her animal was crossing the bridge. Some other participants behaved more relaxed and explored more all over the book, and even held their phones to look around in the environment. For example, one participant said to the other player that his animal was running on the other player's arm. Besides, they frequently looked at their partner's screen. Some said that they cared about how their partners would behave in the game as well as if they could find the correct answer successfully.

Participants paid less attention to the virtual objects in the game compared to the competition game. Most interactions happened in the real-world context explicitly. They already discussed the questions and answers outside the game, so they only needed to control the animal to the correct answer. They would turn to their partners and talked to them directly if they had any questions.

5.6.3 Design Implications

We designed and developed the AR game in both competition and collaboration modes based on previous studies and the participatory design sessions. During the game, we noticed different interaction patterns regarding these two modes. We also noticed some gaps for the current AR social serious game and proposed five design implications for future design.

Figure 5.9 shows a vision of four types of social interactions with the current game: 1) the self-exploration of calculating the exercise by oneself in the virtual world; 2) self-interaction with the other player, as discussing together with the other player; 3) self-interaction with the virtual game world, such as paying attention and following the other player's character in the virtual world or trying out the answers in the virtual world randomly; and 4) self-interaction with the physical objects, as paying attention to the content on the physical book.

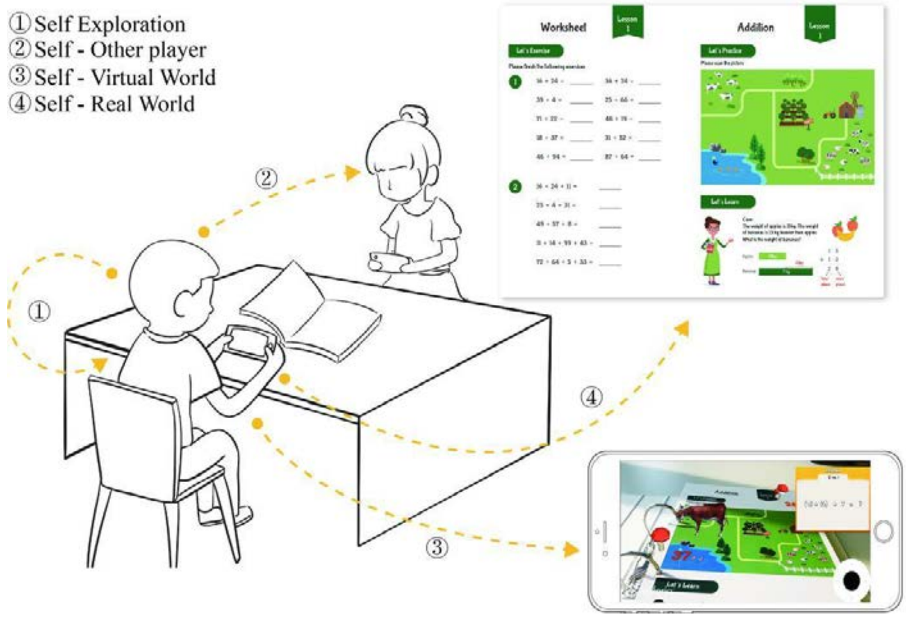


Figure 5.9 A textbook-based AR social learning game for elementary school students to practice mathematics together. Students learn mathematics from the physical textbook and use the mobile device to scan the book page and find virtual content on top of the book to finish the maths exercise. They can see each other in the game in real-time.

These four types of interactions in the AR space could offer a useful lens through which to design and leave the space to improve the AR experience. Here are five design implications based on our findings:

Design for more interactions in the real world in the competition mode.

The competition patterns showed that children focused and immersed themselves more in the game world. They interacted mostly with themselves and with the virtual content but felt less related to the other player and paid less attention to the physical environment. According to SDT, the satisfaction of basic needs for relatedness can lead to increased enjoyment, desire for future play, and recommendation to others (Peng *et al.*, 2012; Przybylski, Rigby, & Ryan, 2010; Ryan, Rigby, & Przybylski, 2006; Tamborini *et al.*, 2010). Therefore, when designing for AR competition, face-to-face interactions should be encouraged by more methods. Besides, the interactions with the physical environment should also be addressed. For example, designers can make the competition happen with a more substantial relation to physical objects such as the textbook (e.g., let children find content in the book).

Design for more interactions in the virtual world in the collaboration mode.

The collaboration patterns showed that participants paid more attention to the objects in the real world. Besides, participants spent significantly more time in the collaboration game. To improve the efficiency in the collaboration mode, virtual objects should offer more useful and effective help. Besides, more information could be collected and shared in the virtual game world since collaboration could trigger more explanation and knowledge sharing (Mullins, Rummel, & Spada, 2011), which are more beneficial for conceptual knowledge.

Design for bridging the gap between the virtual and the real world.

The instructional design is a pedagogical issue that exists in AR learning systems, in terms of how the information should be distributed among two different realities (the AR world and the real world) (Wu *et al.*, 2013). In our study, we also revised the textbook so that the different natural themes on the textbook were related to the animals and environment in the AR world. Besides, it was easier to scan for children, improving the technological issue of recognition in AR systems (Chang *et al.*, 2014).

Design for different learning purposes with competition and collaboration.

In addition to providing a motivating experience for children, learning outcomes are also important in educational games. The findings of this study presented us with different advantages of competition and collaboration modes. In competition mode, children went through the exercises with higher efficiency and were concentrated more. In the collaboration mode, children who were not good at maths had more chances to explore the learning material and to ask questions freely. Different learning activities should be integrated with the two modes to utilize these advantages (Mullins, Rummel, & Spada, 2011).

Design for rich variations

The design patterns in different social contexts provided design concepts for future game design. Participants had their own strategies to finish the game, such as to follow others or to try out different answers. Therefore, more game mechanics should be introduced to make the game rich and varied. For example, to avoid randomly trying out actions by freezing the animal for a while; to avoid cheating as well as making the game more fun by giving animals different features or functions such as speeding up or being invisible.

5.6.4 Limitations of the Study

This study has some limitations and implies several future directions for AR social serious games. First of all, our current study mainly applied self-rated scales as the primary indicator of participants' maths skills. We did not measure the learning effects of the AR game because the current study was a short-term study, and it would be difficult to notice significant improvements. In our previous study (Chapter 3), we measured the correctness rate between doing exercises on the AR game and on paper exercises and found no significant difference. We also purposely decoupled the conceptual knowledge construction with the game mechanics so that these engagement implications could be easily generalized to AR games with different learning domains. This was decided with the consideration of the pedagogical issue of inflexibility of the content in AR systems in previous AR learning systems (Kerawalla *et al.*, 2006). In the next study we can look for more objective measurements of children's academic performance, which could offer a more profound understanding in how the AR game could influence students' learning outcome. Secondly, the findings of this study showed that children had no difficulty in controlling the game. However, sometimes they still lost the animals due to the losing tracking of the image in the book. More considerations should be taken into the usability of the AR features to provide an enjoyable experience for children. Last but not least, the current AR game is a two-player game. The knowledge from this study could be extended to involve more players and see how it would influence their social behaviors. One idea would be to keep the collaboration within the group and extend the competition between two or more groups so that collaboration and competition will happen simultaneously.

5.7 MathBuilder

From the results of the user study in this chapter, we found that the collaboration mode triggered higher perceived relatedness among children. This section is a design exemplar of how we can extend the previous collaboration results into a more full fledged fellowship experience. We present another possibility with an AR-based collaborative learning game for elementary mathematics practicing in the classroom called MathBuilder. MathBuilder is a role-playing AR game where children could build a virtual city together with different characters representing themselves. The game element of role-playing emphasizes more collaborative and "social" skills (Bekker, Schouten, & de Graaf, 2014), which requires teamwork of different characters with "different abilities" to come together. The game element of role-playing allows students to create relationships and be related with others, which can promote the feeling of relatedness (Ntokos and Lamprinou, 2020). The city-building idea was inspired by the famous game, SimCity, also mentioned by children in the participatory design session in Chapter 3. Detailed game concepts are described below.

5.7.1 Game Concepts

MathBuilder was an AR game designed for elementary school children to practice their knowledge in the classroom after taking the lectures based on the original mathematics curriculum. Children would be divided into groups (2-4 per group) and they could choose their own roles in the beginning of the game to represent themselves in the game. During the game, they need to work together to finish the maths exercises and as a result, construct buildings in a virtual world.

MathBuilder consists of a set of tangible toolkits per group and an AR mobile application per child. The set contains physical maps and building cards. Children can scan the building cards and see the virtual 3D buildings popping up on top of the cards through one mobile device (Figure 5.10 and Figure 5.11).

Figure 5.10 Game concepts of MathBuilder.

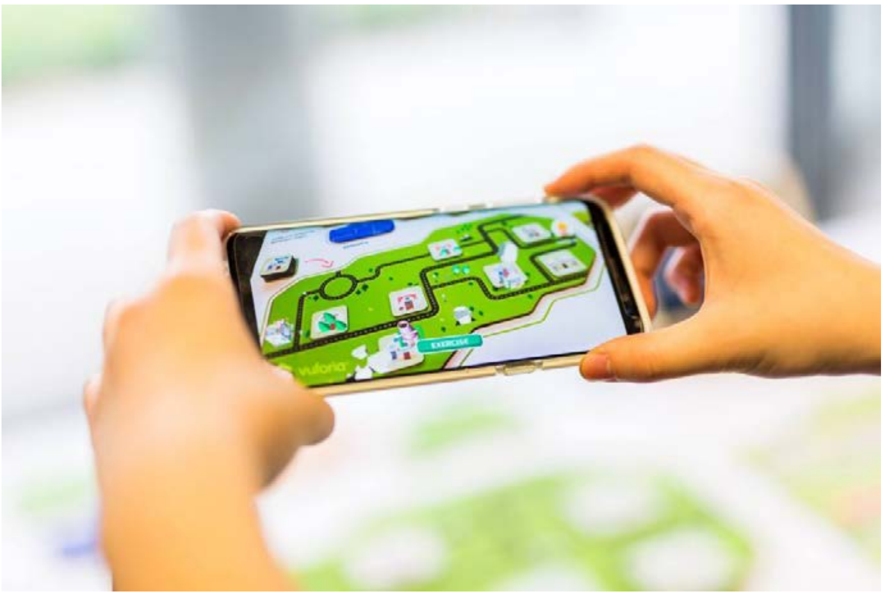


Figure 5.11 Tangible toolkit and virtual 3D buildings in MathBuilder.

- Maps

The physical maps in the game are designed as land areas on which virtual buildings can be built. Students can choose different maps, representing different chapters in the maths textbook at the beginning of the game (Figure 5.12). By scanning the map and the building cards on it with the mobile devices, they can view a brief introduction of the building, including the amount of materials needed for the construction. Then they can decide which building they want to work on and continue with related individual exercises and group tasks.

The tangible toolkits in MathBuilder include physical building cards and maps. Building cards were designed in the size of 65*65 mm with 8 mm round in corners, which makes them comfortable and safe for children to grab. These cards show the figure of different building types, including school, hospital, police station, and private houses. According to these images, students can decide which building they would like to build. Physical maps were designed as land areas where buildings can be built. 3D cartoon elements, including buildings and other small decorations, can be shown above the map to strengthen the realistic sensation. Each map represents a chapter in the maths textbook so students can unlock them one by one throughout the year.

Figure 5.12 Choose maps for different chapters in the maths textbook.

- Individual Tasks

Children need to choose their own roles they want to play in the construction process (bricklayer, carpenter, painter, or designer). Then they have to collect different unique building materials related to their roles by finishing their individual exercises. For example, a bricklayer can only collect bricks by finishing exercises. All team members should finish their individual exercises first. Individual exercises will be assigned to students randomly for practicing the knowledge they have just learned. They will receive immediate feedback and explanation after finishing each exercise. See Figure 5.13.

Figure 5.13 Individual tasks and feedback.

- Collaboration

Children can also help each other or ask for help during the game. After each of them finishes the individual exercises and collects enough materials, they can move on to the group tasks, which are more difficult and require group discussions. The final constructed buildings will be shown in various levels according to the accuracy of the final group answers. See Figure 5.14.

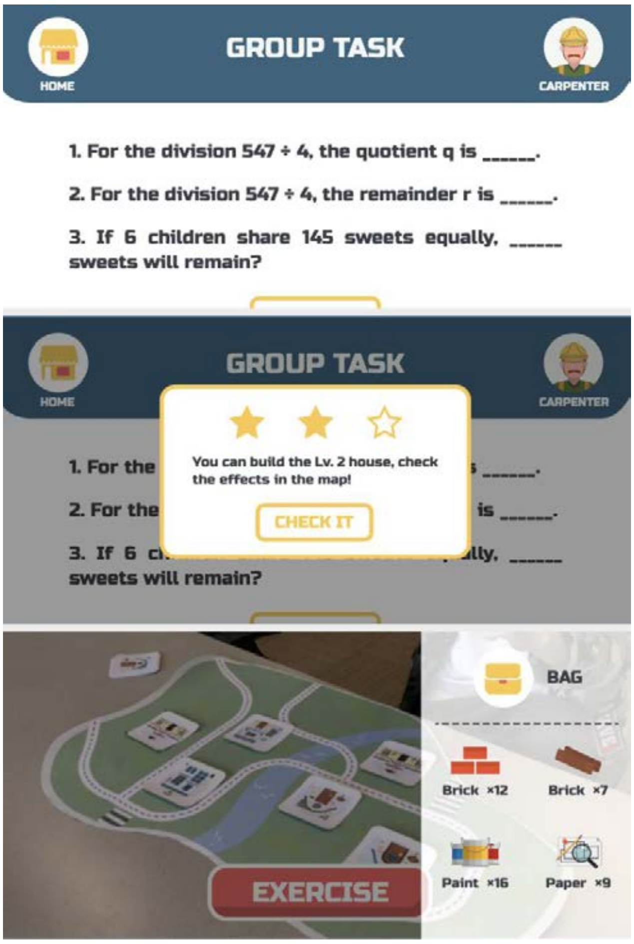


Figure 5.14 Collaboration (group task, progress, material collection).

5.7.2 Insights from a Preliminary User Study

A preliminary user study was carried out to study the motivational effects of the MathBuilder on students and the social effects of the collaboration. Eight students from group 5 in an elementary school in the Netherlands participated in the study (see Figure 5.15). During the experiment, two students were randomly assigned in a group to play the game. They would talk about and interact with the game for ten minutes before ending the session. After each game session, we asked students to reflect on their previous experience in the maths classroom and their collaboration during the AR game.

Regarding the previous experience in the maths classroom, students mentioned that sometimes their teachers had little time to pay enough attention to them, and it was even considered a waste of time to ask teachers for help with the large number of students who were all in need of answers. Some students preferred taking their homework and questions home to their parents for help. One student indicated that he felt that he could not ask the teacher questions, as it might negatively influence the impression the teacher would have on him, leading to worse results over time.

MathBuilder allowed children to rely on each other for the help during the learning process. With MathBuilder, children were not only motivated to help others by working in a team, but also had a clear idea to whom they could go and ask for help. Overall, children enjoyed exploring the game and were immediately attracted by the new mechanic of scanning objects and virtual objects. This was something that was referred to as being “very cool” many times. Children also mentioned that MathBuilder had improved the sense of collaboration among them. They liked working together in the game, whereas they could not do at home with the games they were currently playing. It should be noted here that in MathBuilder, the collaboration and discussion among children were not limited to the level of game functions but also happened at the level of doing actual maths exercises with discussions about the maths content itself.

Children also expressed that the AR functions in MathBuilder could be open up to more possibilities. There could be more to explore for them, and the possibilities for asynchronous interactions could provide a lot more depth to their collaboration. For example, it could allow them to experience the cities in real-time, and let other groups see their results.

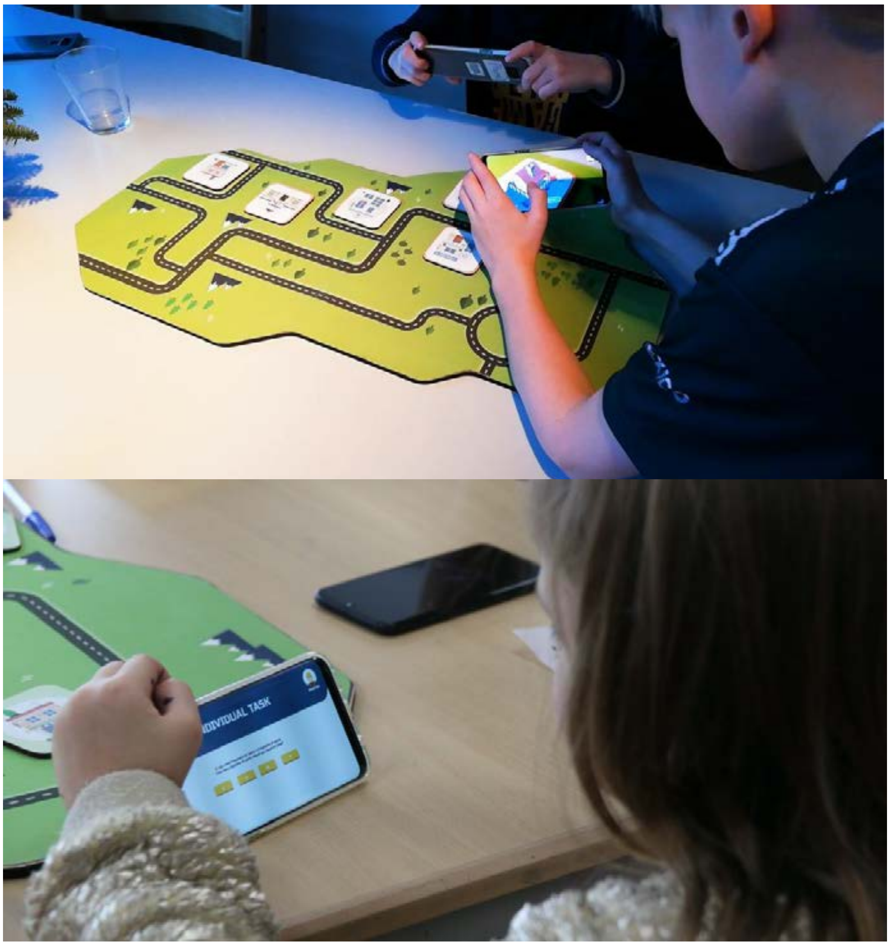


Figure 5.15 Preliminary user study.

5.8 Conclusion

In conclusion, in this study, we designed and developed the new game concepts of a textbook-based AR social serious game, See Me Roar, for elementary school children to practice mathematics together. Our game combined the social elements under the AR context to extend the empirical understandings for the design of AR social serious games. We identified different perceptions of children and different play patterns under different social contexts in the AR environment. Based on these findings, we provided general solutions to problems that game designers may encounter when designing for specific aspects of AR social serious games and proposed design implications that offer rich design spaces in applying the AR game to deliver a more engaging and effective learning experience.

We found different outcomes generated from these two social contexts. We found that participants would focus and immerse more in the game world in the competition game, while they might extend the boundaries of the game to the real world and to incorporate the other player in the collaboration game. However, we are not urged to draw a conclusion of which one is better in AR games. Instead, our findings could be applied to support the development of social AR serious games and new forms of social play in a shared-world AR system. This research should be seen as an exploration into the engaging potential of AR social serious games, with for this chapter a particular focus on the way competition and collaboration impacted the shared augmented play space for learning, and the way that in turn correlated with other social dimensions.

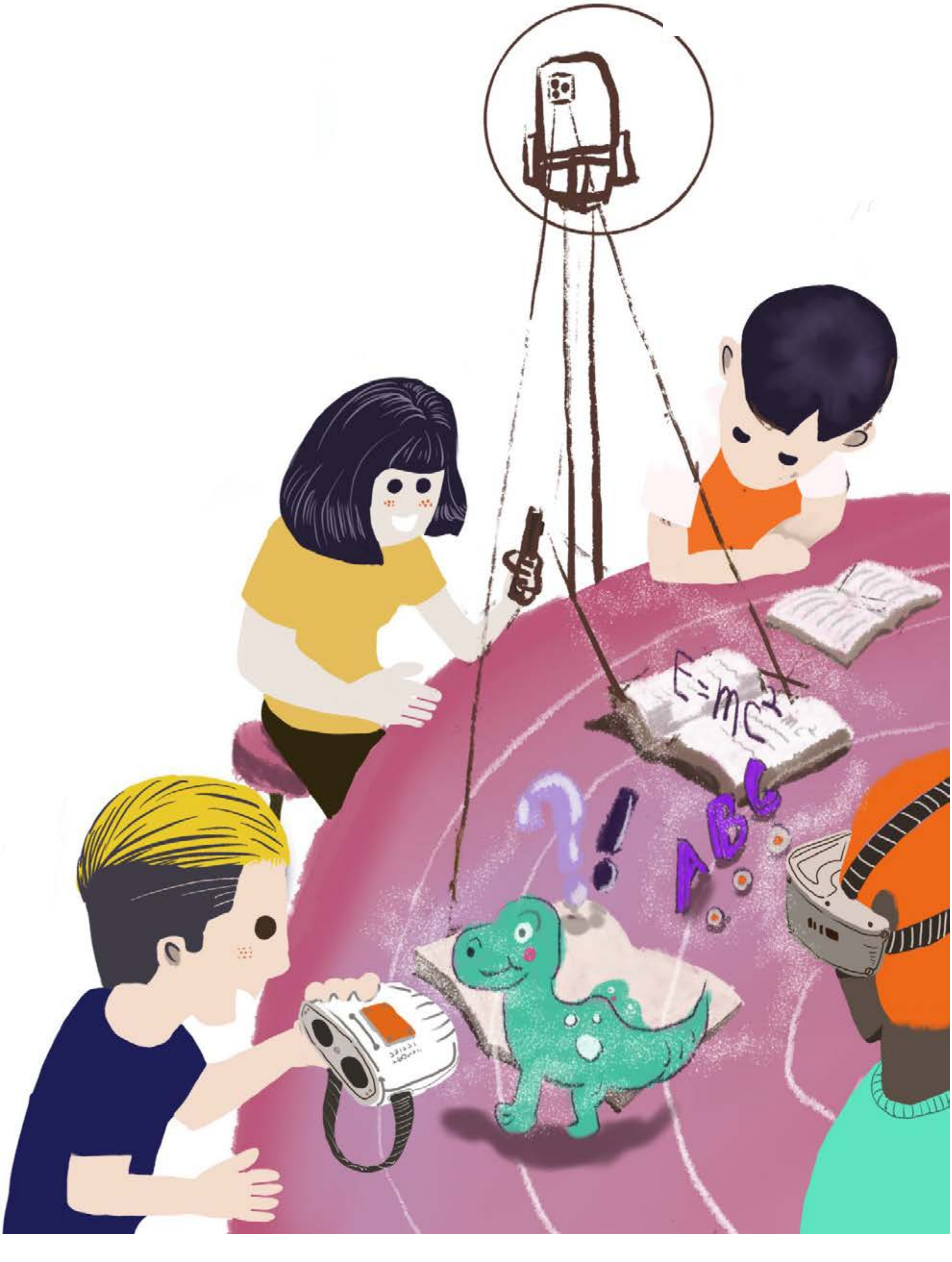
In addition, we also presented one possibility for an AR-based collaborative learning game for the elementary maths classroom, MathBuilder, aiming at motivating students in maths learning activities based on standard curriculum and encouraging them to collaborate with each other during the maths exercises practice.

As mentioned in Chapter 3, in our research, we would take the ideas generated from each iteration to a next game idea to fill in features inspired by perceived competence, relatedness, and autonomy step by step. Therefore, in the next chapter, we will fill the theoretical framework with autonomy-inspired features to build a systematic understanding of the design space of serious AR games and the ways to improve motivation for learning.

CHAPTER

SIX

DESIGN AND EVALUATION OF AN AUTONOMY-SUPPORTIVE AR SERIOUS GAME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Chapter 6: Design and Evaluation of an Autonomy-Supportive AR Serious Game

6.1 Introduction

In previous chapters, we explored the design guidelines for AR serious games with features inspired by notions of perceived competence and relatedness. We identified directions for improvement for the experience, including looking for more objective measurements of children's academic performance, taking more considerations into the usability of the current AR game to prevent the frustration from losing tracking of the image in the book, etc. We took these considerations into the study in this chapter.

This chapter focuses on the design and evaluation of the autonomy-supportive AR serious game. We designed the AR game with four different versions (see Figure 6.1) based on the results from the previous studies and tested pathways to immerse children to explore and play in an AR fantasy world. We conducted a 2 (task choice vs. no choice) x 2 (game story vs. no game story) experiment with 81 participants (Mean age = 8.82) to identify possible effects on motivation while performing maths exercises in AR settings. We articulated our design process for other designers and researchers to incorporate it for similar problems, providing insights into how to design an AR serious game to improve the learning experience with the aid of autonomy-supportive mechanics.

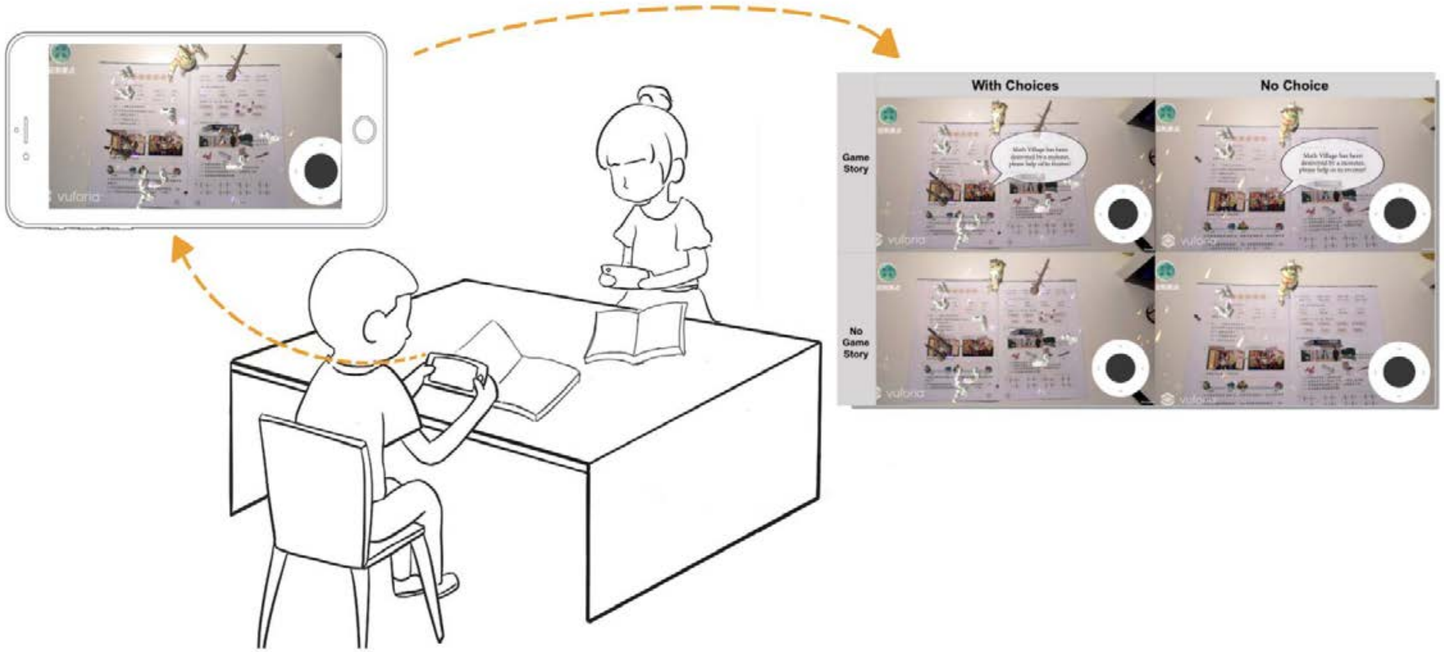

Figure 6.1 Children use mobile devices to scan their mathematics textbooks to play the AR game through four different game versions.

6.2 Background

6.2.1 Self-Determination Theory and Research Questions

In our previous studies, we have designed and evaluated a competence-supportive game and a relatedness-supportive game based on SDT, investigating how children reacted to two different interaction styles as well as two different feedback mechanics when performing exercises in the AR setting, and learning the effect of social interactions in AR serious games on children's learning experience. In the current study, we focus on the design and evaluation of an autonomy-supportive AR serious game.

Autonomy within SDT is defined as a sense of volition or willingness when doing a task (Ryan, Rigby, & Przybylski, 2006). In the educational domain, children are autonomous when they "pursue their interests, study to satisfy their curiosity, and volitionally engage themselves in their schoolwork" (Su and Reeve, 2011, pp.160). Autonomy-supportive activities, such as displaying non-controlling language or providing children the time they need for self-paced learning (Reeve, 2009), have the potential to enhance intrinsic motivation and lead to higher academic achievement (Guay, Ratelle, & Chana, 2008; Vansteenkiste *et al.*, 2004; Reeve *et al.*, 2004).

Methods to enhance autonomy include providing choice and informational feedback as reward and meaningful instruction (Ryan, Rigby, & Przybylski, 2006; Sailer *et al.*, 2017). The provision for choice allows users to choose between several courses of action (Przybylski, Rigby, & Ryan, 2010). For example, an autonomy-supportive game offers players choice of different routes to an end in terms of what tasks they choose, the skills they acquire, and how their characters appear in the game (Przybylski, Rigby, & Ryan, 2010; Sailer *et al.*, 2017). In addition, the choice provided should also lead to meaningful informational feedback. In an autonomy-supportive game, the game story could play an important role to help players experience their own actions as meaningful and volitionally engaging (Rigby and Ryan, 2011). Therefore, in our study, we integrated task choice and game story into the AR settings to investigate their effects on stimulating motivation. We aimed to answer the third research question of this thesis:

RQ3. How to apply game design mechanics to AR serious games based on notions of perceived autonomy in Self-determination theory to enhance children's learning motivation and experience?

6.2.2 Task Choice in AR Serious Games

Offering task choice refers to providing choice among options and invitations to participants to self-direct their own tasks (Su and Reeve, 2011). According to SDT, choice is a facilitating condition that makes an individual find a self-congruent activity and perceive himself/herself as the causal origin of that activity (Deci, Koestner, & Ryan, 1999). Therefore, in our autonomy-supportive game, we provided children with a sense of control and freedom to move their characters freely in the game world.

However, SDT research also highlights that autonomy should not be equated with the mere presence of choice (Deterding, 2015). In addition, to enhance the perceived autonomy, a game should be designed to respond dynamically to an individual's task choice without constraining them (Ryan, Rigby, & Przybylski, 2006). When the sense of task choice or control is diminished during an action, the perceived autonomy will be similarly diminished and the intrinsic motivation may be undermined (Deci, Koestner, & Ryan, 1999). In parallel, too much choice may lead to cognitive overload during the experience, which is one of the most frequently reported AR design challenges (Deterding, 2015; Klopfer and Squire, 2008; Perry *et al.*, 2008). The willingness to play a particular game may vary in the autonomy afforded within the game, such as the degree of choice one has over the sequence of tasks or actions undertaken (Reeve *et al.*, 2004). While Smeddinck *et al.* (2016) conducted a study investigating the impact of different difficulty choice modes and found that the type of difficulty modes had an impact on perceived autonomy, where most players expressed a preference for manual difficulty choices, but the differences in perceived autonomy did not impact the overall game experience significantly. Hence, we were curious to find out the impact on the experience of children by providing children different levels of exploration, we formed our first sub research question in this study:

- 3.1 What are the effects of providing children opportunities for exploration in terms of task choice in AR serious games?

6.2.3 Game Story in AR Serious Games

Children may not learn sufficiently due to the lack of intrinsic motivation or have low confidence in their learning activities, resulting in performing in an undesirable way (Antonaci, Klemke, & Specht, 2015). A game story is one of the motivational tools to solve this problem (Ardito *et al.*, 2010), which adds sense to the learning task, giving the learning activity a specific form to be linked to the context. The meta-analysis of Wouters and van Oostendorp (2013) also showed that the game story had a positive effect on motivation, and it might play an important role in keeping the player engaged and motivated.

In the context of AR serious games, previous research also suggested driving the player interaction and learning through gamified stories or narratives (Dunleavy, 2014), which could provide the structure and rationale for the AR experience and impact the quality of the experience profoundly (Klopfer and Squire, 2008; Perry et al., 2008). Early in 2004, Malaka et al., presented a mobile outdoor AR system for assisting users in learning history through an interactive story-telling game. Other related work includes an AR serious game where a game started with a narrator explaining the archaeological site of Knossos and asking the students to find the specific location in Greece (Zikas et al., 2016); a multiplayer AR serious game to increase the intrinsic motivation into historical education, using the game story to integrate their game topics of trading, migrations, and wars (Plecher et al., 2019); an AR location-based game for cultural heritage education, exploring the game narrative structural techniques suitable for cultural heritage sites (Haahr, 2017).

While the game story may have the potential to enhance motivation, research indicated that the fantasy game environment might lead to lower learning achievements (van der Spek et al., 2014). Adams et al. (2012) also found no positive effect of the game story on learning performance. Hence, more should be done to create an effective game story, including research on a successful game story in respect to specific learner groups, such as for children, and empirical research that connects the game story with other instructional design methods for serious games (Antonaci, Klemke, & Specht, 2015). Therefore, we proposed our second sub research question in this study:

– 3.2 What are the effects of providing children elements of fantasy in terms of game story in AR serious games?

6.3 Game Design

To answer the research questions, we designed and developed a new AR game prototype for elementary school children to do their mathematics exercises. The game was then made into four different versions to measure the main and interaction effects (task choice vs. no task choice; game story vs. no game story). This section introduces the outcomes of our previous research phases and the design rationale for the current game, and discusses on how the design stages are related to each other.

6.3.1 Research Phases

In our first study (Chapter 3), we explored the game concepts by conducting a participatory design and a preliminary study. Upon this study, we came up with our basic game concepts that 3D animals could be found in a school textbook waiting for children's help to solve mathematics problems. Children could use mobile devices to scan the book page and find these 3D animals to interact with by screen-touch input. Upon completing the exercise, children would receive immediate feedback showing the right or wrong answers. The results of the exploration study showed that AR game exercises were considered more fun than traditional paper exercises in both two cultures. Children were motivated by the game concepts of helping the AR animals while doing mathematics. Regarding the learning performance, there was no significant difference between the paper or AR game on their exercise scores, indicating that the AR game did not have negative influence on children's learning task performance.

In the second study (Chapter 4), we iterated the AR game based on the design insights from the first study and the feeling of competence in SDT. We designed two different interaction styles as well as two different feedback mechanics to investigate how children reacted when performing maths exercises. In this study, we found a significant effect of feedback mechanics on motivation, where children liked collecting animals and seeing how they populated the 3D map over a simpler 2D bar. There was no significant effect of screen-touch or tangible interaction on motivation, while screen-touch interaction was perceived as easier to master.

Then, in Chapter 5, we designed and implemented a new game considering the design implications obtained from the first and second studies and the feeling of relatedness in SDT, learning the effect of social interactions in AR serious games on children. To find inspiration for the concepts of the AR game, we conducted another participatory design session and came up with the collaboration mode and the competition mode, utilizing the real-time interaction that AR affords (Azuma, 1997). The results of the study showed that children felt more related to each other in the collaboration mode but were more concentrated in the competition mode. We also collected the ideas and suggestions from children and found that the virtual exploration on the physical book was the most appreciated feature. In addition, children were willing to see richer content in the AR world, such as buildings and human character. Then, we extended the collaboration results into a multiplayer role-playing and city-building game with human characters and buildings.

Now it is time to iterate the AR game once again, testing how to immerse children in a fantasy world to explore and play with AR settings. In the following section we will go into details about the design of the autonomy-supportive game.

6.3.2 Game Concepts

In line with our previous games, the game was again designed for elementary school children to do digitally augmented mathematics exercises on top of their school textbooks. In the game, children hold a mobile device to scan the textbook and see a fantasy world (a ruined village ruined and a human character to represent the player) appearing on top of the book page. In line with MathBuilder, we included human avatars and buildings in the newly developed game. Each of the ruins in the village carries a maths exercise. The ruins would be recovered by children answering the maths exercises correctly. Children can move their characters around the book in the game with the screen-touch interaction. Once they step on the ruin, the corresponding maths exercise will show up. The types of digital maths exercises are related to the types of exercise underneath it on the book. For example, if there is an addition exercise on the book (e.g., 325 + 464 = ?), an addition exercise will show up in the digital area close to it (e.g., 317 + 432 = ?). If the exercise is answered correctly, the ruin will recover to either buildings, plants, or other accessories in the village. If the exercise is answered incorrectly, the ruin will stay the same and children can come back to answer the question again at any time. Children answer the digital exercises on the mobile device directly. They can do the calculations mentally or on paper first. The game was designed with Unity 3D and the Vuforia Engine and played on Samsung S8s. The exercises were chosen from a Chinese maths textbook for grade 3, including addition, subtraction, and problem solving.

6.3.3 Design of the Autonomy-Supportive Features

According to SDT, autonomy refers to the feeling of volition or willingness to do a task (Deci, Koestner, & Ryan, 1999; Ryan and Deci, 2000b). The experience of autonomy is high when the task is done for personal interests or values (Su and Reeve, 2011). Thus, the current game already provides children feelings of autonomy by allowing them to choose to answer the exercises or not and to walk freely all around in the game without limits.

Exploration

In the PLEX framework, exploration is defined as investigating an object or situation. In our game, we provide children with free choice to explore in the AR world. Children can control the character to move freely around the book to any point according to their preferences on the looks of the ruins or the types of the exercises on the book. Once children step on a point, the corresponding maths exercise will show up. Children can choose to answer it or not.

Fantasy

In the PLEX framework, fantasy refers to an imagined experience. In our game, children can choose their own avatars (human characters) in the beginning of the game, which will represent themselves during the game. Then they will receive a gamified story world to immerse themselves in exploring and playing with the fantasy in the game.

In the meantime, to answer the research questions on the effects of providing children elements of exploration in terms of task choice and fantasy in terms of game story in AR serious games, we further developed the game concepts into four different versions. Below are the detailed game mechanics.

- Version 1: Task Choice + Game Story

When children scan the textbook with a mobile device, they start with a game story that a village, called Maths Village, has been destroyed by “monsters”. The concept of “monsters” was hypothesized to provide more competence and also applied in an AR-based maths game before (Cheng *et al.*, 2019). The game story will guide the children to help recover the village (Figure 6.2a). Then children see the fantasy world popping up on top of the book page, full of ruins. There are 10 ruins with luminous points (Figure 6.2b). Each of the ruins carries a maths exercise related to the maths exercise on the physical book underneath it. Children can control the character to move freely around the book to any point they want. Once children step on the point, the corresponding maths exercise will show up. Children can choose to answer it or not. If the exercise is answered correctly, the ruin will recover to either a building, plants, or other accessories in the village (Figure 6.2c). If the exercise is answered incorrectly, the ruin will stay the same and children can come back to answer the question again at any time. After finishing the 10 exercises correctly, children will see the entire village looks normal again.

- Version 2: No Task Choice + Game Story

In this version, the game story part remains the same as version 1 (Figure 6.2d). Different from version 1, children can only see one ruin from the first exercise (Figure 6.2e). Children have to answer the exercise pertaining to the ruin correctly to unlock the next ruin (Figure 6.2f). Consequently, children will recover the ruin one by one from the first exercise to the tenth in a system-directed order. All the other elements remain the same as in version 1.

- Version 3: Task Choice + No Game Story

Unlike versions 1 & 2, in this version, children won't receive any story-line during the entire game. Children see their character standing up in the middle of the book, surrounded by ruins without any hint as to what they mean. The visual representations of ruins are kept in to make sure that the other version is not liked more purely on visual aesthetics. Children can move their character freely around the book and recover the village by answering the exercises. Except for the lack of a game story, both the game mechanics and the AR elements like 3D models and animations are the same as in version 1.

- Version 4: No Task Choice + No Game Story

In this version, children have to start from answering the first exercise as in version 2 and receive no game story as in version 3. The process of version 4 is similar to the traditional paper exercises except for the augmented shell showing a ruin around the exercises.

Figure 6.2 Autonomy game: 2a: game story with task choice version, 2b: children can see all the ruin points in the beginning in the version with task choice, 2c: some parts of the ruins recover to buildings and plants, 2d: game stories with no choice version, 2e: children can only see one ruin point in the beginning in the version with no choice, 2f: children have to answer the exercises one by one.

6.3.4 Implementation of the AR Game

Figure 6.3 shows the software architecture of the AR game. First, the camera on the mobile device captured the image targets on the physical book, which was already stored in the Vuforia database. The virtual objects would be rendered on users' devices and overlaid on top of the book. Users could interact with the virtual objects with the user interface on their devices or interacting with the physical book directly.

As mentioned above, we used the Vuforia platform to implement AR functionality. Vuforia is a free software development kit for tracking images with the support for Unity 3D. In the beginning of our research in 2016, Vuforia was the most common and advanced SDK to create AR functionality. Vuforia SDK has various functions, including image recognition, multi-image recognition, object recognition, and word recognition. In our prototypes, we mainly used image recognition. The platform would detect and track the image targets from the physical book and match them with the objects in the virtual world (e.g., a virtual elephant). See Figure 6.4 for part of the code in Vuforia to track the image targets. Then the virtual objects would be rendered in Unity 3D engine. We used Photon[17] networking package in Unity to connect the players in the AR world (see Figure 6.5 for the connection code). We used the BG Database from BansheeGz[18] to store the game narratives and the maths exercises. The virtual objects were assets chosen from the Unity Asset Store[19].

[17] **Photon:** https://www.photonengine.com/pun

[18] **BansheeGz:** http://www.bansheegz.com/

[19] **Unity Asset** https://assetstore.unity.com/

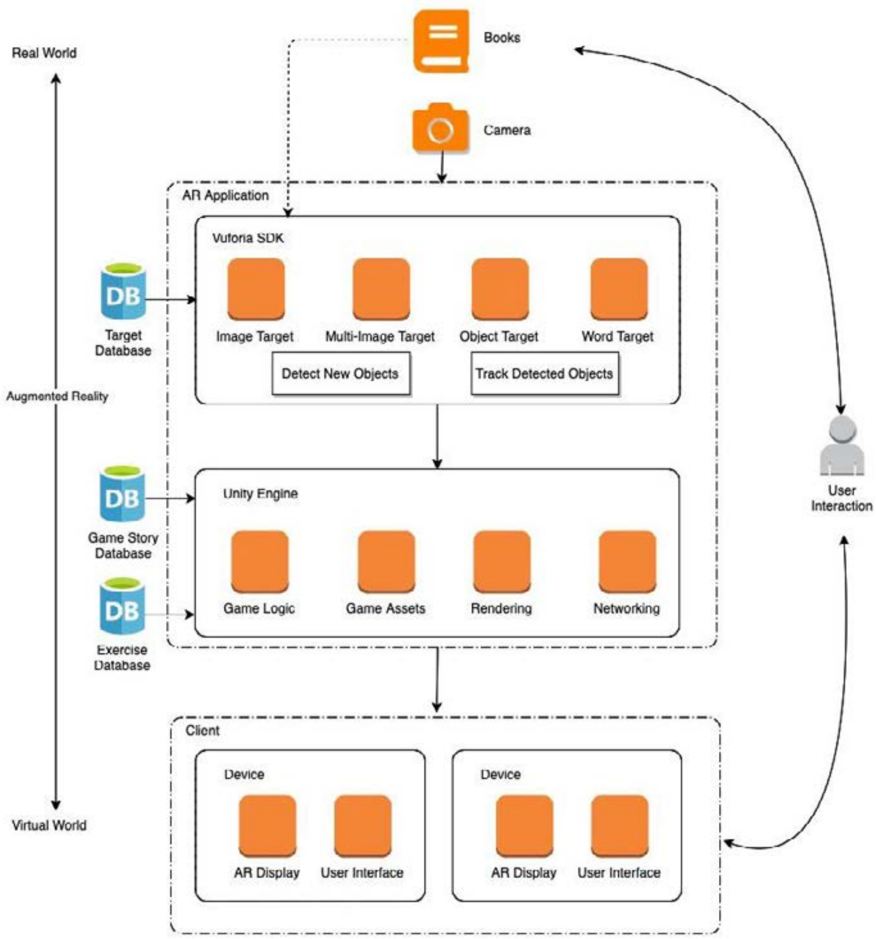

Figure 6.3 Game architecture.

```
protected virtual void OnTrackingFound()
{
    if (mTrackableBehaviour)
    {
        var rendererComponents = mTrackableBehaviour.GetComponentsInChildren<Renderer>(true);
        var colliderComponents = mTrackableBehaviour.GetComponentsInChildren<Collider>(true);
        var canvasComponents = mTrackableBehaviour.GetComponentsInChildren<Canvas>(true);

        // Enable rendering:
        foreach (var component in rendererComponents)
            component.enabled = true;

        // Enable colliders:
        foreach (var component in colliderComponents)
            component.enabled = true;

        // Enable canvas':
        foreach (var component in canvasComponents)
            component.enabled = true;
    }
}
```

Figure 6.4 Part of the code in Vuforia SDK for tracking the image target.

```
void Start()
{
    ConnectToPhoton();
}

void ConnectToPhoton()
{
    connectionStatus.text = "Connecting...";
    PhotonNetwork.ConnectUsingSettings();
}
```

Figure 6.5 Example code in Unity for connecting to Photon servers.

Although the game concepts were changing over time, we reused a lot of our code in the four studies with meaningful classes, methods, variable names, and in-line comments. We decoupled the 3D assets, maths exercises, and the game storylines with the code to be more effective in development. For example, we only needed to change the 3D animals to human characters from study 3 in Chapter 5 to study 4 in this chapter.

6.4 User Study

The goal of this study was to understand how to design AR serious games with the aid of autonomy-supportive game mechanics for elementary school children, and the effect thereof on learning and motivation. In this section, we describe the design of the user study and the setup.

6.4.1 Participants and Procedure

We conducted an experiment with a 2 (free choice vs. no task choice) x 2 (game story provided vs. no game story) between-subjects design within the context of a textbook-based mathematics game for elementary school children. We recruited 96 participants in total and received 81 available results from 42 boys and 37 girls aged (2 chose not to identify their gender) 7-10 years old (Mean = 8.82, SD = 0.83). The rest of the participants did not complete the entire intervention or questionnaire in the study. Participants were recruited from an after-school center a week before the study with informed consent.

In our competence study (Chapter 4), we found that although tangible interactions had the potential of improving the AR experience, we did not find significant evidence to support it, so we kept the screen-touch interaction to keep the game simple in the current study. Children could move their character by the joystick on the bottom-right corner. In addition, to avoid frustration for children when they lose track of the image on the book or lose their characters, we designed a “Back to Center” button on the top-left corner of the screen. When the game character is too far away from the view, children can click the button to get it back to the center. Figure 6.6 on the left shows the experiment setup, on the right shows the basic interactions in the game.

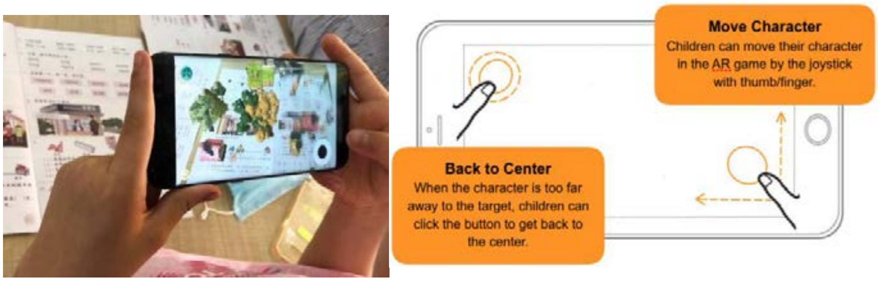

Figure 6.6 Left: experiment setup; right: basic interactions.

In the beginning of the study, participants received a brief introduction about the study purposes and procedures (8-9 children in one group concurrently based on the time they signed up for the study). Then participants took a knowledge pre-test with 10 exercises similar to the exercises on the book with pen and paper. Subsequently, participants were asked to write down their age and gender on the paper. Then, participants were randomly assigned to one of the following four conditions: version 1) with a game story and task choice, version 2) with a game story and no task choice, version 3) no game story with task choice, and version 4) no game story and no task choice (see Table 6.1 for the number of participants per condition).

Table 6.1 Number of participants per condition.

Game Story	**Task choice, n (%)**		**Total, n (%)**
	With Task Choice	No Choice	
With Story	22 (27.2)	21 (25.9)	43 (53.1)
No Story	20 (24.7)	18 (22.2)	38 (46.9)
Total	42	39	81

Knowledge pre-test ($F(3,77) = 1.47$, $p = 0.228$), gender ($F(3,75) = 0.23$, $p = 0.872$), and age ($F(3,77) = 2.45$, $p = 0.070$) were all distributed equally across the 4 conditions. A significant positive correlation between the knowledge pre-test and age was found ($r = 0.55$, $p = 0.000$). See Table 6.2.

Then, participants were given 10 minutes to explore the AR game. After completing of the game, participants reported their perceived autonomy, perceived competence, perceived relatedness, and enjoyment level of the AR game (more details are described in the following section). Lastly, participants were interviewed in groups about their perception and evaluation of the overall experience. We also used a screen-recording app to record the entire game play session of participants. The time for the study was approximately 30 minutes.

Table 6.2 Sample characteristics (N=81).

Variables	Value, n (%)	Mean (SD)	Range
Gender		---	---
Boy	42 (51.9)	---	---
Girl	37 (45.7)	---	---
Unknown	2 (2.5)	---	---
Age (years)		8.82 (0.83)	
7	2 (2.5)		
8	30 (37.0)		
9	29 (35.8)		
10	20 (24.7)		
Pre-test score		8.69 (1.29)	3 - 10

6.4.2 Measurements

It is challenging to collect reliable opinions from young children in user studies (Airey *et al.*, 2002; Bell, 2007; Hanna, Risden, & Alexander, 1997), where children might find it difficult to understand the questions or the scales (Airey *et al.*, 2002). In addition, children could be influenced by the desire to please adults in user studies (Airey *et al.*, 2002; Bell, 2007; Hall, Hume, & Tazzyman, 2016).

Thus, our research has been looking for different paths in measuring children's experience during the game empirically. In our first study in Chapter 3, we applied the original version of the PENS scale but had trouble of children understanding the 7-point Likert scale. In our second study in Chapter 4, we designed an animated scale to measure PENS for children aged 7 to 8 years old. We found potential of the animated scale for measuring younger children's learning experience. However, we received criticism for using an unreliable scale and suggestions of applying a more qualitative method with children. Hence, in our third study in Chapter 5, we applied a one-item scale and looked deeper from the interviews and observations. In this study, the scale of our participants was larger (81 participants), and the age range was wider (7-10 years old, mean age = 8.82). We decided to apply the PENS scale with a 5-point Likert scale, and explained each item one by one to the children in groups.

The PENS scale has been developed based on SDT for assessing game experiences, including items for perceived competence to assess the perceived efficacy playing the game, perceived relatedness to assess the sense of social connections, and perceived autonomy to assess the sense of self-determined behaviors (Deci and Ryan, 1985; Rigby and Ryan, 2007). We also measured the enjoyment level with 7 items adapted from the IMI (Ryan, 1982; Ryan, Mims, & Koestner, 1983). Below are the detailed items in the scales.

- Perceived Competence: We included 3 items from PENS to measure perceived competence (e.g., "My ability to play the game is well matched with the game's challenges"), answered from 1 (completely disagree) to 5 (completely agree) and were transformed into a mean score (alpha = 0.631, mean = 4.34).
- Perceived Relatedness: There are 3 items in PENS to evaluate perceived relatedness (e.g., "I find the relationships I form in this game important"), answered from 1 (completely disagree) to 5 (completely agree) and were transformed into a mean score (alpha = 0.425, mean = 3.85). The alpha is low in perceived relatedness, which might be due to the different understandings of the relationships in the game (with other players or with the players in the game world).
- Perceived Autonomy: We also measured the perceived autonomy with 3 items from PENS (e.g., "The game provides me with interesting options and task choice"), answered from 1 (completely disagree) to 5 (completely

agree) and were transformed into a mean score (alpha = 0.526, mean = 4.43).

- Enjoyment Level: The enjoyment level was assessed with 7 items adapted from IMI (e.g., "I enjoyed playing this game very much"), answered from 1 (completely disagree) to 5 (completely agree) and were transformed into a mean score (alpha = 0.834, mean = 4.51).

6.5 Results

6.5.1 Results on PENS and IMI

Regression analyzes were conducted to test the effects of task choice and game story on perceived competence, relatedness, autonomy, and enjoyment level.

- Competence: The main effect of game story was significant on perceived competence ($F(3,77) = 7.80$, $p = 0.007$, $d = 0.09$), where the score was higher in the version with the game story (Mean = 4.52) than the version with no game story (Mean = 4.13). The two-way interaction between the game story and task choice was significant ($F(3,77) = 7.10$, $p = 0.009$, $d = 0.08$). When there was a game story, the version with no task choice (Mean = 4.73) was perceived as providing a higher feeling of competence than the version with task choice (Mean = 4.32). When there was no game story, the version with no task choice (Mean = 3.96) was perceived as providing a lower feeling of competence than the version with task choice (Mean = 4.30). The main effect of task choice was not significant. See Figure 6.7 top-left.
- Relatedness: The main effect of the game story was significant on perceived relatedness ($F(3,77) = 8.97$, $p = 0.004$, $d = 0.10$), where the version game story (Mean = 4.09) scored higher than with no game story version (Mean = 3.57). The main effect of task choice and the two-way interaction between the game story and task choice were not significant. See Figure 6.7 top-right.

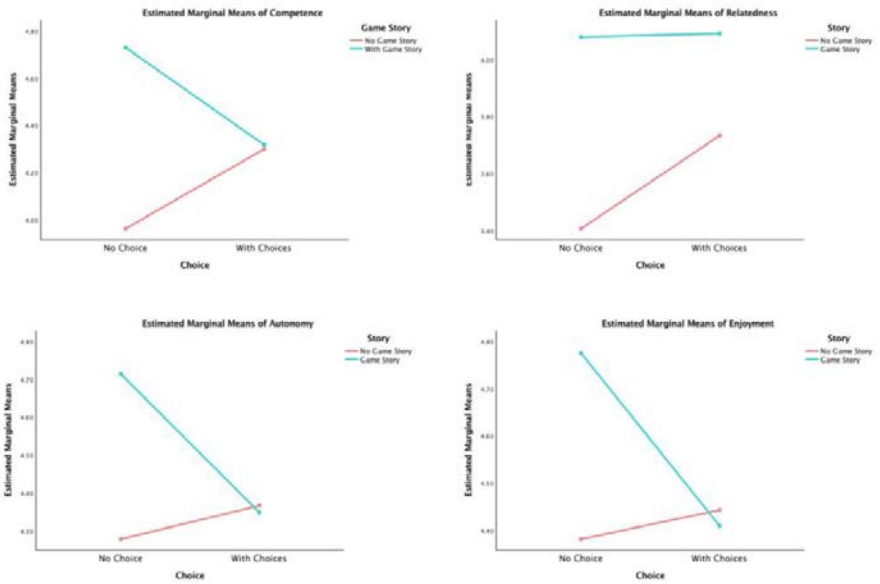

Figure 6.7 Effects of task choice and game story on perceived competence (top-left), perceived relatedness (top-right), perceived autonomy (bottom-left), and enjoyment level (bottom-right).

- Autonomy: There was no significant main effect of task choice and game story on perceived autonomy. Neither was there a significant effect on the two-way interaction between the game story and task choice. See Figure 6.7 bottom-left.
- Enjoyment Level: There was no significant main effect of task choice and game story on the enjoyment level, and no significant interaction effect. See Figure 6.7 bottom-right.

However, the interaction effect showed a trend ($F(3,77) = 2.98$, $p = 0.089$. In the game conditions with a game story, the version with no task choice (Mean = 4.78) resulted in a higher enjoyment level compared to the version with task choice (Mean = 4.41). When there was no game story, then task choice (Mean = 4.44) led to a higher enjoyment level than without task choice (Mean=4.38). This corresponds with the higher feeling of competence and relatedness for these versions, since significant positive correlations between the enjoyment level and perceived competence (r = 0.41, p=0.000), autonomy (r = 0.55, p = 0.000), and relatedness (r = 0.33, p = 0.002) were found.

6.5.2 Learning Task Performance

We checked participants' correctness rate in answering the exercises from the playing log as the in-game learning task performance with the AR game and identified 73 valid data sets. Eight logs were lost because some participants accidentally stopped the screen recording. A significant main effect was found for task choice on the correctness rate, F(3,69) = 1.89, p = 0.000, d = 0.29: the correctness rate was higher in the version with no task choice (Mean = 9.34) than with task choice (Mean = 7.97). This could be explained by the no task choice version providing participants a more efficient and clearer path to complete the task than the version with task choice. Besides, the type of exercises in the AR game was multiple task choice and participants could keep trying until the exercises were answered correctly. No significant main effect was found for game story. Neither were any interaction effects found between task choice and game story. See Table 6.3 below.

We also found that the correctness rate was correlated with the knowledge pre-test (r = 0.60, p = 0.000) and age (r = 0.31, p = 0.008). There was no other significant correlation.

Figure 6.8 is the distribution of the scores of perceived competence, relatedness, autonomy, enjoyment level (score from 1-5), and task performance (score from 0-10) among the four versions. From the visualization we can see that participants enjoyed playing the proposed AR game in general, while high scores occurred most frequently in Version 2.

Table 6.3 Effects of task choice and game story on learning task performance.

Variables	d(f)	F	Mean Difference	P value	Mean	SE	95% CI
Game Story	1	1.888	-0.352	0.174	---	---	---
Game story	---	---	---	---	8.482	0.180	8.12 to 8.84
No game story	---	---	---	---	8.834	0.182	8.47 to 9.20
Task Choice	1	28.597	-1.369	0.000	---	---	---
Task choice	---	---	---	---	7.974	0.177	7.62 to 8.33
No task choice	---	---	---	---	9.343	0.185	8.97 to 9.71
Game Story * Task Choice	69	1.684	----	0.199	---	---	---
Game story * task choice	---	---	---	---	7.632	0.251	7.13 to 8.13
Game story * no task choice	---	---	---	---	9.333	0.258	8.82 to 9.85
No game story * task choice	---	---	---	---	8.316	0.251	7.82 to 8.82
No game story * no task choice	---	---	---	---	9.353	0.265	8.82 to 9.88

Figure 6.8 The distribution of the scores of perceived competence, relatedness, autonomy, enjoyment level, and learning performance among the four versions.

6.5.3 Interview Results

After collecting the questionnaire, we conducted an interview with participants in the groups. We asked participants the differences between doing exercises with the AR game and doing exercises on paper. Some of the participants thought that the AR game was more fun to them as: they experienced it more like a game (e.g., "we can play games while finishing some exercises", P17; "I have the similar game at home, but not with the camera open, it's fun to look around", P43); they felt less stressed (e.g., "the paper exercises made me feel more nervous", P9; "I believed it could help me to get better scores in exams, because I can be more relaxed", P 47); they received the feedback immediately after answering the questions (e.g., "buildings are showing up and there are animations after finishing the exercises if I'm correct", P32; "it's not like on the paper, I'm not sure if my answer is correct or not", P 33); and they could see other children's progress and help each other during the game (e.g., "I can see what others are doing if I scan their books, it is fun", P48; "I finished my game quickly and I knew who was slower and I could help", P61).

On the contrary, some participants preferred to do the exercises on paper, mainly because it was faster or easier. They were more familiar with this type of exercises in their homework at home and school (e.g., "it's like the homework I'm doing every day, and I'm good at it", P6; "the paper version saves time, you don't need to walk around", P68).

6.6 Discussion and Limitations

6.6.1 Discussion of the Results

This study aimed to find design paradigms for AR serious games with autonomy-supportive mechanics to improve motivation and engagement in the context of elementary mathematics learning. To this end, based on prior empirical research and SDT theory, we investigated the effects of two strategies, exploration in terms of task choice and fantasy in terms of game story, on perceived competence, relatedness, autonomy, enjoyment level, and learning task performance.

First of all, there appeared to be a main effect of game story on the perceived competence and perceived relatedness, where in the version with a game story the participants perceived higher competence and relatedness than the version with the no game story. This is in line with previous studies that games with a fantasy environment offered a stronger game experience, while the fantasy game environment was achieved at the cost of lower learning gains (van der Spek *et al.*, 2014). However, in our study, the fantasy environment did not negatively influence the learning task performance. Hence, this can be considered an effective strategy to increase confidence and make children feel more related to the fantasy game world in AR serious games.

With regard to the task choice, we found a significant main effect on learning task performance. The correctness rate was significantly higher in the version with no task choice than with task choice. From the observation of the study, we noticed that in the version with no task choice, participants had to finish one exercise to unlock the next exercise, following a clear path to complete the task. While in the version where participants could choose their own path, they spent more time wondering where to go next.

In addition, the two-way interaction between the game story and task choice was significant on perceived competence. When there was no task choice, the game story made participants feel more competent than without the game story. While when a choice in task sequence was provided, the game story version triggered lower feelings of competence. Similarly, the two-way interaction between the game story and task choice approached significance on enjoyment level. When there was no choice, the task choice would stimulate a higher enjoyment level. When participants could choose their own path, the effect of task choice had a negative effect on enjoyment level. Designing serious games for young children is different from designing for adults. Too many task choices and game narratives may burden children's cognitive load and they will consequently get confused about what to do next.

In our study, game story and task choice resulted in neither significant main effects nor significant interaction effects on perceived autonomy. In all four conditions, participants experienced autonomy by moving their characters freely on the book. The difference was whether they could choose their own path completing the task or only follow the path directed by the game system. The results implied that this would not influence children's perceived autonomy while doing exercises.

We also observed that participants often talked to the children next to them. They tried to move their character to the other children's textbook, and scan the other's books to check their progress and find more exercises in the digital world. Thus, the opportunity to experience social connections and interactions with others could be more likely increased with the proposed AR environment. The interview results also revealed several reasons why children experienced fun with the AR game, such as the immediate feedback they could receive, less pressure they felt, and the social interactions happened among them in the shared space. In the meantime, some children still appreciated the easiness and effectiveness of just doing exercises on paper. There is no one-size-fits-all when designing AR serious games for children. What we were doing was to learn from the results of our previous studies to iterate the new design, and investigate the design guidelines for applying game design mechanics to AR learning. In the following section we propose five design recommendations to design AR serious games with the aid of autonomy-supportive mechanics for elementary school children.

6.6.2 Design Recommendations

Integrating the game story into the physical object.

AR learning systems face a pedagogical issue regarding the gap between the AR world and the instructional materials (Klopfer and Squire, 2008; Wu *et al.*, 2013). In our previous design (Chapter 5) we revised the physical textbook and made the images and themes on the book be related to the content (animals, plants, etc.) in the AR game. In the current study, we came back to the common textbook children used daily. We connected the book and the game by connecting the book content and the exercises children would receive in the game world (for example, there was a virtual point on top of the book, the digital exercise of that virtual point was the same exercise on the book). We made the book become a fantasy world with a game story.

Our study also implied that the game story resulted in higher perceived competence and relatedness than without the game story. We utilized the advantage of AR to connect the content on the physical book and content in the digital world. When designing AR serious games, one could improve the learning experience for children by a integrating game story in the instructions. Specifically, the game story can be related to the physical objects from the real environment in AR settings. For example, in our cases, we augmented and added fantasy to the traditional textbook children use daily. The normal textbook can be extended and changed to different stories and themes, and children will step into the “magic circle” when they open the book and become immersed in the imaginary world (Paras, 2005). In our game, we match the types of exercises children will receive when they step on certain points (ruin points in the game) in the digital game with the types of exercises under that point on the physical book, so that children know which exercises they will get and can choose the exercises they want to answer autonomously. However, during the experiment, we found that children did not pay much attention to the content on the physical book page but focused more on the digital ruins they wanted to save first. For creating a more immersive learning experience, one can align the game stories with the content on the textbook to make the connection between the virtual world and the real world stronger.

Moderating the degree of task choice.

There are also challenges in the AR learning environment, where children could be cognitively overloaded by a large amount of information they encounter and the complex tasks they have to accomplish (Wu *et al.*, 2013). Our result also indicated that the free task choice did not always result in a better learning experience. Although the integration of choice has the potential to enhance motivation, the degree of choice should be moderated to lower the cognitive load. When children were presented with all the digital content at once, it hindered their effectiveness especially in the beginning when they were not familiar with the game. In some cases, starting from a simple option and then gradually unlocking more options when the children get familiar with the game could lead to better results. The game can also provide more explicit visual guidance such as the direction to the next point, the difficulty of the exercises, etc.

Considering the interaction effect between the game story and the task choice.

The interaction effect between the game story and task choice showed that when there was a game story, children who had to follow the system-directed path enjoyed the AR experience more than those who were offered free choice of the order to complete the tasks. The enjoyment level reached the lowest when there were no gamified instructions and participants had to complete the exercises in a system-directed order in the AR game. Thus, to better improve the overall experience, the appropriate degree of task choice and the game story should be considered together, offering children with meaningful goals and instructions to make sense of their actions and the consequences. The result was also similar to our second study (Chapter 4), where the enjoyment level reached the lowest when children had to operate the tangible interactions with a non-diegetic 2D progress bar.

Creating opportunities for social interactions.

Another design recommendation that aligns well with AR affordances is the ability to create opportunities for social interaction. In our study, children were curious about the others' progress and tried to scan others' books. They would turn to others for help during the game and vice versa. When they finished their own tasks, they would try to move their characters to the book page of the person sitting next to them. Therefore, we see a strong potential to create a shared augmented space where children can communicate naturally. In our relatedness-supportive game, we suggested an interesting direction to extend the two-player game to involve more players too. To build a fun AR experience, the game may allow children to choose the exercises from other children's books so that they could answer the exercises competitively. Or children have the opportunity to finish the exercises together with their teammates. Additionally, the game story could become topics to discuss among children. For example, they could decorate the classroom based on the theme in the book, which makes the game experience more immersive and motivating.

Facilitating children to get back to the main game quickly.

An autonomy-supportive AR game should allow children to act freely and in the way they like. For example, some children would like to scan other objects on the table or in the room for a while rather than just the textbook or be curious to walk to some places that are far away from the book. In our study, we also observed that children frequently moved their textbooks to look for virtual objects from different angles. The feature of AR showing different things from different perspectives allows children to explore the way they like, making the interaction richer and the experience more fun. However, it might take longer for children when they want to get back to the exercises. To prevent the frustration from losing track of the main goal of the game, we designed a “Back to Center” in the current game. During the experiment, we observed that children used the “Back to Center” frequently to get back to the center of the book when they were too far away or lost the characters within their sights. Therefore, when designing an autonomy-supportive AR game, one should always take into account how to help children to get back to the main goal of the game quickly and effectively. This also aligns well with the design recommendations given by Endsley et al., (2017) that the AR interfaces should make it easy for players to recall the items that are outside the field of view.

6.6.3 Limitations of the Study

The proposed AR game has the potential to solve the problems identified for traditional serious games, including the lack of motivational effect, the difficulty to be integrated into the classroom settings and curriculum, and social isolation. However, limitations exist in this study. Firstly, we recruited participants in an after-school center so that they were from different schools and classes. Although we conducted a knowledge pre-test and made sure the participants were distributed equally across the four conditions, we should match the exercises better to children’s knowledge level in our future study. Secondly, according to our interview results, some children were attracted by the new form of AR technology, while some preferred doing exercises on paper, which they were familiar with more. A long-term study could help to alleviate this kind of effect. Lastly, in our study, we found no significant result on perceived autonomy. This might because participants experienced autonomy in all the conditions by moving their characters freely on the book and seeing the same animated AR world. With the proposed design guidelines, we could delve deeper into how to influence the perceived autonomy in the learning process.

6.7 Conclusion

While AR serious games have become an emerging solution to positively influence the learning motivation and experience for elementary school children, the systematic and empirically tested design guidelines remain unexplored. In our study, we undertook an extensive research through design process and communicated the methods and the outcomes of prior studies. Then we developed an AR game with autonomy-supportive mechanics for mathematics learning and conducted an experiment to identify their effects. We learned from our previous experiments and tried to avoid prior limitations, especially in experimental methodology. Regarding the measurement, we applied a quantitative method using questionnaires from SDT-based PENS and IMI. In addition, we also applied qualitative methods such as interviews, observations, and in-game logs. We tested children's mathematics skills before they started the game with traditional paper exercises and calculated their in-game scores to see the differences among different game versions. Our results indicated that the version with a game story and easy choice path improved the learning experience the most. Based on our empirical findings, we extracted five design guidelines on how to design AR serious games to improve children's learning experience.

Till now, we built our framework based on SDT and PLEX to understand which design patterns are suitable in AR serious game settings to stimulate learning motivation for children. We completed one study for exploring the possibilities of applying AR learning games among children from different cultures. We conducted three studies for investigating features based on the framework step by step. Although we designed a more or less new game for every step, we tried to take the implications generated from each iteration to the next game idea. In the next chapter, we will make a conclusion of this research, including the overall research process, the theoretical investigations on SDT and PLEX, the design and implementation process of multiple AR prototypes, and the responses to the research questions with the systematical and empirically tested design guidelines for AR serious games.

CHAPTER

SEVEN

CONCLUSIONS, LIMITATIONS, AND OPTIONS FOR FUTURE WORK

Chapter 7: Conclusions, Limitations, and Options for Future Work

In this research, we applied both a research through design and an empirical research for design methodology, exploring the design space for AR serious games based on SDT. We realized multiple AR serious games to improve the learning motivation and learning experience for elementary school children. In this chapter, we first look at our overall research process. Then we summarize our theoretical investigations of the design of AR serious games inspired by SDT and the PLEX to inspire more works on designing AR serious games. Thirdly we look back to the design and implementation process of the multiple AR serious game prototypes in our research. After that, we respond to the research questions formulated in Chapter 1 based on the results of our four studies. Specifically, we generalize a set of design guidelines using examples and discuss how our designs fit in with the latest developments, which are intended to help future related designs in AR serious games for elementary school children. In the end of the chapter, we discuss the limitations of this research and options for future work.

7.1 Research Process

Figure 7.1 describes the research process of our study, including different activities and results. The research process consists of three parts: theoretical research, artifact development, and empirical research.

At the beginning of this thesis, we identified the societal problems for elementary school children, e.g., the lack of motivation in traditional learning materials; concerns of children using digital games and social media. Then we reviewed previous work of the state of the art in solving the identified educational problem and explained the issues of existing solutions, e.g., integrating serious games in the classroom; missing a systematic and empirically tested approach towards the design of AR serious games. We formulated the main purpose of this research as to explore:

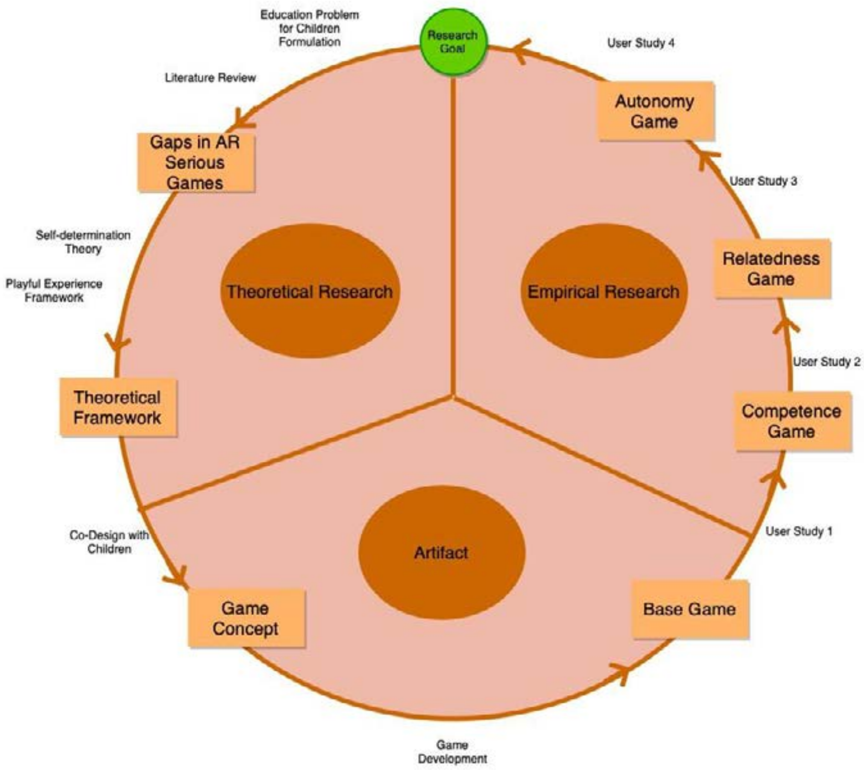

Figure 7.1 Research process.

Then we proposed a structured framework based on SDT and PLEX by mapping the suitable playful categories of the PLEX to SDT needs, based on the meaning and explanation of the three psychological needs (see Figure 1.6 in Chapter 1 and the detailed explanation in Chapter 2).

In the second part of our research, we first generated a number of design concepts with AR features based on the proposed theoretical framework together with our target users by conducting participatory design and low-tech prototyping sessions. Then we developed the game prototypes with the Vuforia plugin for AR features in the Unity 3D engine. We iterated the game design based on the three psychological needs in SDT and with an increasing level of detail as more insights were obtained through the user studies. As a result of the artifact development process, we realized four different AR game prototypes.

The last part of the research led to the extraction of design guidelines on how to design engaging AR serious games. We answered the research questions (see Chapter 1) separately with the design guidelines respectively to address the research goal. In addition, the reflection on our experiments also shed light on the methods to collect reliable opinions from young children.

7.2 Theoretical Research

One of the benefits of the research through design method is that design researchers provide solutions to bridge the general aspects of the behavioral theory and models to a specific context of use and set of target users (Zimmerman, Forlizzi, & Evenson, 2007). In our research, we tried to translate SDT principles into the design of AR serious games for elementary school children practicing mathematics. SDT is a widely applied theory in game research in Human-Computer Interaction (HCI). However, it remains unclear how HCI game scholars applied and engaged with the theory (Tyack and Mekler, 2020). In our research, we systematically contextualized our main research question within SDT as:

How to design AR serious games based on notions of perceived competence, relatedness, and autonomy in Self-determination theory to enhance children's learning motivation and experience?

Specifically, we applied each psychological need within SDT to AR features, exploring the design space of AR serious games, and raised three novel research questions:

RQ1. How to incorporate AR-specific elements in serious games based on notions of perceived competence in Self-determination theory to enhance children's learning motivation and experience?

RQ2. How to amplify the advantages of social interactions in AR serious games based on notions of perceived relatedness in Self-determination theory to enhance children's learning motivation and experience?

RQ3. How to apply game design mechanics to AR serious games based on notions of perceived autonomy in Self-determination theory to enhance children's learning motivation and experience?

We mapped the six categories of the PLEX framework to the three psychological needs of SDT based on their definition and explanation. We also reviewed the previous studies in AR serious games. Figure 7.2 shows the framework of our research including SDT, PLEX framework, and game mechanics.

Competence

In our competence study, children were challenged with different types of interaction styles (screen-touch interaction vs. tangible interaction). They received different types of completion as immediate feedback (a 2D progress bar vs. a 3D progress map).

- Challenge. In our game, we challenged children with two different types of interactions. Children interacted with the 3D animals in the game to find the maths exercises either with tangible interaction by turning and lifting their physical textbooks or with screen-touch interaction by pointing on the screen. The challenge from the tangible interaction was perceived by the participants as more difficult and it required more effort than the screen-touch interaction. However, there was no significant difference in perceived competence between the two types of interactions. Different levels of challenges may not influence the competence directly, especially when the skills of children change over time.

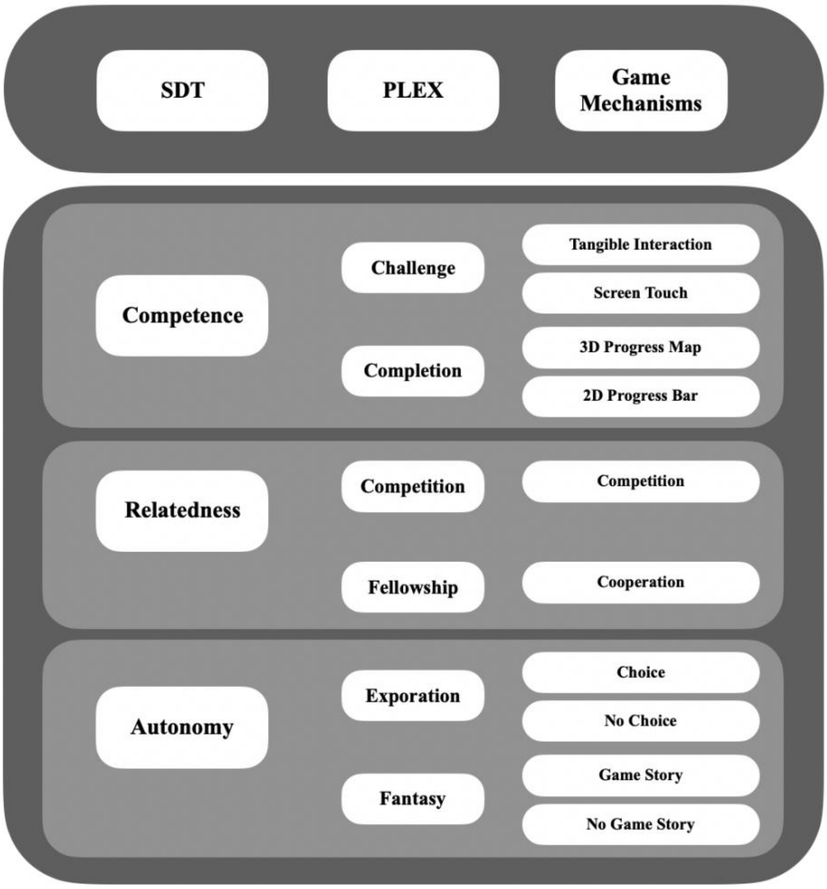

Figure 7.2 Research framework based on SDT, PLEX, and game mechanics.

– Completion. In our game, we provided children with different types of feedback as the closure of the task. Children received immediate feedback after finishing the exercise either by a 2D progress bar or by a 3D progress map. With the 3D progress map, if the exercise was answered correctly, children would see the animals appearing on the map. The 2D progress bar was analogous to how they were used in traditional digital games. Completion played a more important role in terms of acquiring competence in our study. According to the study results, the 3D progress map triggered the feeling of competence significantly more than the 2D progress bar.

Relatedness

In our game, the social interactions were enabled to produce feelings of relatedness: children either tried to win the game in the competition, or worked together as a team and experienced the fellowship.

- Competition. In our game, children could see each other's animals on top of their textbooks, they had to compete with each other on who was faster to get the correct answer. Based on the results of our study, in the competition mode, children no longer paid attention to the other person nor to the physical objects in the real world. Although they were still interacting with the others face-to-face, they perceived lower relatedness and felt less connected.
- Fellowship. In our game, we offered children the opportunity to cooperate with each other. Children worked together with each other to complete the task. To be more specific, one of them could only see the exercise and the other one could only see the answers. They discussed what they saw to finish the task. Based on our study results, children perceived higher relatedness when they could work together as a team and paid more attention to the others and objects in the real world.

We found no significant correlation between the perceived relatedness and the self-rated maths skills, gender, age, as well as the time spent in the game in both modes of the current AR game.

Autonomy

In our game, children were provided with different levels of opportunities to explore (free choice vs. system-directed order) in a fantasized game world (with a game story vs. no game story).

- Exploration. In our game, children explored the game with two different levels: the higher degree of exploration offered children free choice to control their characters to move freely around the book to any point they wanted; while with the lower degree of exploration, children had no choice but could only see one point from the first exercise and had to answer the exercise correctly to unlock the next point in a system-directed order. From the results we found that these two levels of exploration had an effect on children's in-game maths performance but not on their perceived autonomy. The features, such as investigating the virtual objects, choosing to answer the exercises or not, and talking freely to the others in the same room, might already provide children the feeling of autonomy, while the order of exercises to be answered in the game was not that much important to them anymore.
- Fantasy. In our game, there were two fantasy modes, one with a game story and one without. In the version with a game story, children started the game by receiving a fantasized story with narratives. In the version without a game story, children did not receive any story-line during the entire game. The rest of the AR elements, such as the visual representations of buildings, characters etc., stayed the same to make sure that the other version was not liked more purely on visual aesthetics. Our study result showed that although the version with a game story resulted in higher competence and relatedness than the version without a game story, different fantasy modes had no significant effect in children's perceived autonomy. The AR elements like the buildings, plants, and human characters already provided a sufficient feeling of an imagined experience to children. They might make up a game story by themselves with their own understanding and imagination. We had a similar finding in the study of MathBuilder, where half of the participants were provided with the background story of the game before the game started, while the other half had to explore by themselves. We found that all participants ended up

operating fluently without any question, regardless of the amount of prior explanation offered.

In this section, we summarized our theoretical investigations on SDT and PLEX with AR game functions. We also discovered some unanticipated effects of AR game functions on competence, relatedness, and autonomy. In the next section, the multiple prototypes of our AR games with the features inspired by the three psychological needs will be presented.

7.3 Implementation of the AR Serious Games

Based on the theoretical model, we designed and developed four AR prototypes in our research: the base game of See Me Roar, the competence-inspired game, the relatedness-inspired game, and the autonomy-inspired game. Besides, we also presented an extra collaborative multiplayer AR game for maths classes called MathBuilder.

Our initial idea was to iterate the base game step by step with features inspired by the three psychological needs. However, during the research, we changed our plan into designing a more or less new game for every iteration based on the insights gained from the previous study, because this approach could lead to more interesting design insights. Below are the features we found that could be improved in the base game and the changes we made in the prototypes in different studies:

- Difficulties in image recognition:

In our base game, children generally reported troubles scanning the paper with their mobile devices and easily lost focus of the AR animals. In the second prototype, we switched the maths textbook over to an image on a single piece of paper so that there would be less trouble for children to scan and see the AR content (Figure 7.3a). Since the concept of the game was still to gamify a maths textbook, in the third prototype, we re-designed the maths textbook with larger scan areas (Figure 7.3b). In the fourth prototype, we switched back to the normal school textbook because the Vuforia engine had been updated in the meantime, and was now able to detect the smaller image targets and targets at a greater distance (Figure 7.3c).

Figure 7.3 (a) Image target for study 2; (b) Image target for study 3; (c) Image target for study 4.

- More control over the animals:

In our base game, we observed children trying to touch the virtual animals with their hands and turn the physical books around. They also required to have more control over the animals according to the interview results. In our second study, we designed two different ways to control the movement of the animals, and the results implied that screen-touch interaction was enough for the current AR prototype. Thus, in the third study, we kept applying the screen-touch interaction with a joystick to move the animals. In the fourth study, we stayed with the same joystick. In case that children might lose the focus of their characters in the book, we also designed a “Back to Center” button in the game. Whenever the button was clicked, the character would immediately come back to the center of the game world.

- Collection of the animals in the game:

In the study of the base game, children expressed that they did not want their animals to disappear in the game world. Hence, in our second study, we allowed children to collect the animals on a 3D progress map (Figure 7.4a). The study results showed that this kind of diegetic feedback triggered a higher enjoyment level. In our third study, children could choose an animal from a preset collection to play as in the game (Figure 7.4b). After answering correctly, the animals would play a cheerful animation. Children kept asking for more types of 3D elements such as buildings, places, and “people” walking in the game. In our fourth study, we designed human characters and a village with buildings and plants (Figure 7.4c). The village would be recovered from ruins to its original look by children answering the exercises correctly. Children received this kind of diegetic feedback to know if their answers were correct or not.

- Desire for social interactions:

In our base game, we saw that children shared their screens with others and communicated a lot with others next to them. Our relatedness-inspired study enabled competition and collaboration interactions among children. As a result, we found that children felt more connected when they were collaborating. We also presented a collaborative multiplayer AR game called MathBuilder for an elementary school maths class. In our fourth study, children could either compete with each other to see who was faster to finish the task or discuss the maths exercises and help each other. There was a shared augmented space where children could communicate naturally.

Figure 7.4 (a) 3D progress map in study 2; (b) Choose an animal in study 3; (c) Human character and 3D buildings in study 4.

7.4 Answers to the Research Questions

7.4.1 Design Guidelines

To answer the research questions, we employed the SDT-based measurements (PENS, IMI, and IoCiS) to evaluate the effect of different AR-specific elements, social interactions, and game design mechanics on children's learning motivation and learning experience. We concluded a set of design guidelines using examples and reflected on how our designs could be better situated within the latest developments in AR technology.

RQ1. How to incorporate AR-specific elements in serious games based on notions of perceived competence in Self-determination theory to enhance children's learning motivation and experience?

- 1.1 How can we integrate different types of challenges in AR serious games for children, and which of these types work better?

In our research, we specifically integrated different types of interactions as different types of challenges for children and investigated the effects of them on children. Based on the research findings, we proposed two design guidelines:

Design Guideline 1. Mainly applying screen-touch interaction in AR serious games.

In our competence study in Chapter 4, our results indicated no significant difference between the screen-touch and the tangible interactions, while the screen-touch interaction was perceived as more effective and easier to understand. Therefore, for AR serious games, we suggest applying the screen-touch interaction. In our prototypes, we used a joystick to control the movement and found that children aged 7 to 10 had no difficulty interacting with the joystick. To offer more control to children, the speed of the movement could be changed by holding the joystick for a longer time or clicking on an extra button.

Design Guideline 2. Applying tangible interaction as an alternative solution.

Although tangible interaction was more difficult and required more effort from children, some of them experienced more fun during game play, especially after they fully understood how the game worked. In Chapter 4 we discussed that the proper amount of challenges could help keep children engaged in the game to avoid boredom, especially when their skills and abilities were improving over time. Besides, we offered children the opportunity to control the speed of the movement, which was asked by children in the base game, by lifting the image target with different degrees. Hence, tangible interaction has the potential to motivate and immerse children in a more fun experience in AR serious games.

We also suggest that to provide meaningful tangible interaction to children, AR designers should use tools that are a part of the game world. One of such tools is, for example, in our game, the textbook the animals are standing on top of. We noticed that children were able to make meaningful real-world analogue actions by controlling the virtual content with the textbook directly, and through that, understand the direct feedback corresponding to their actions. Model target recognition available in Vuforia could be used to enrich the tangible interaction as well. For example, AR designers could allow users to use real-world objects, for example, using a real apple to interact with a virtual elephant.

Moreover, as discussed in Chapter 4, tangible interaction could also be applied to develop children's fine motor skills such as hand-eye coordination and spatial abilities. In our autonomy-inspired study in Chapter 6, we also observed that children frequently moved their textbooks looking for virtual objects from different angles. Some children would also like to scan other objects on the table or in the room for a while rather than just the textbook or be curious to explore some places far away from the book. The feature of AR showing different things from different perspectives allows children to explore the way they like, making the interactions richer and the experience more fun, as well as bringing potential add-on benefits to children. However, it may take longer for children to get back to the main tasks. Therefore, we suggest AR designers to always take into account how to help children to get back to the main objective of the game quickly and effectively.

- 1.2 How can we integrate different types of completion in AR serious games for children, and which of these types work better?

In our study, we investigated different types of feedback to provide the feeling of completion to children. Based on the findings of our study, we proposed one design guideline:

Design Guideline 3. Leveraging diegetic feedback of AR to increase motivation.

We suggest that AR designers utilize the special affordances of AR to generate a diegetic mixed reality experience and create an immersive play space. The results of our competence-inspired study indicated that in the AR environment, the diegetic feedback triggered significantly higher motivation over the non-diegetic feedback. Then our follow-up prototypes all applied the diegetic way to provide feedback. The diegetic feedback could be shown on the textbook (the image target) itself, or on extra physical objects. This kind of diegetic feedback could avoid the situation where children perceive the feedback as controlling and/or see the activity as a task they have to perform rather than a game they want to play. The setting of filling up a natural pasture with animals or building a city could be felt as more self-determined than following the game rules to completion.

RQ2. How to amplify the advantages of social interactions in AR serious games based on notions of perceived relatedness in Self-determination theory to enhance children's learning motivation and experience?

- **2.1** Which types of social interactions in terms of competition and fellowship should we integrate into AR serious games for children?

In our research, we integrated collaboration and competition as social interactions in our games. Based on the research findings, we proposed two design guidelines:

Design Guideline 4. Encouraging collaboration.

In our literature review in Chapter 2, we suggested creating opportunities for social interactions in AR serious games. It not only aligns well with the ability of AR to enable natural communication among children, but also with the intention of children to communicate and discuss with each other during the game, according to the observations in our field studies. Therefore, we offered two types of social interactions to children in our relatedness-inspired study.

The results of the study showed that the collaboration mode resulted in higher perceived relatedness for children than the competition mode. Children felt close to their partners because they were helping each other and they could understand what they were talking about as a team. We also noticed that children would discuss with each other during the collaboration game. As discussed in Chapter 5, children perceived teamwork to be fun and liked the presence of each other in the game, leading to more communications in the real world. They shared with each other what they were looking at and made decisions on one answer together. Besides, as observed in our base game and the autonomy-inspired game, children would turn to others for help during the game and vice versa. They were curious about their peers' progress and tried to scan each other's books. When they finished their own tasks, they would move their characters to the others' book pages as well. Consequently, also as mentioned before, we see strong potential to create a shared augmented space in the game for children to work together. Collaboration could be the first choice when designing for social interactions in AR serious games.

Design Guideline 5. Designing for real-time competition.

Although the collaboration could lead to more active communications and discussions, the results of the study also showed that children finished the learning tasks faster and were concentrated more in the competition mode. In the context of an educational game, the efficiency of learning is equally important besides the motivating experience. Thus, competitive elements could be included if efficiency is an important factor in reaching the learning goals of the game. According to the section of related work in Chapter 5, elements such as leaderboards and scores were the most commonly used features for competition in existing AR serious games, which, however, are not specific for AR settings. We suggest that AR designers design for real-time competition, and that the results of the competition should be embedded in the diegetic feedback. For example, children can see what the others' characters or animals are doing or how many buildings are already built in the cities of other children in real time. The real-time competition could be perceived as more fun and more directly by young children compared to leaderboards or scores.

– 2.2 How do children perceive their social interactions in terms of competition and fellowship in AR serious games?

In our research, we also focused on how children perceived their relationships with each other under different social interactions in both the virtual world and the physical world. Based on the research findings, we proposed another design guideline:

Design Guideline 6. Designing for appropriate social interactions in AR serious games.

Children might perceive their social interactions differently in terms of competition and fellowship. In our relatedness-inspired study in Chapter 5, we found three different patterns in the competition mode and collaboration mode each. We also summarized four types of social interactions that existed in the AR game, including self-exploration, self-interaction with the other player, self-interaction with the virtual world, and self-interaction with the real world. Consequently, when designing for social interactions in AR serious games, it is important to distinguish these two modes to generate the most appropriate experience for children.

To be more specific, in the competition mode, children might be more focused on the virtual game world and ignore the other players as well as the real world. Thus, AR designers could design for more interactions in the real world to facilitate face-to-face interaction as well as interaction with the physical environment. For example, there could be a task to find content on the physical book page, where children need to read the book page to find it. Or the game allows children to choose the exercises from other children's books so that they can initiate a conversation naturally.

In the collaboration mode, children might play the AR game in a way similar to a real-world game and spend significantly more time. Therefore, in the collaboration mode, AR designers could design for more interactions in the virtual world to improve learning efficiency and provide more complex and conceptual knowledge. For example, they have to solve a puzzle by collecting pieces of digital information in the game together. Children take time to think about the information and encourage each other.

RQ3. How to apply game design mechanics to AR serious games based on notions of perceived autonomy in Self-determination theory to enhance children's learning motivation and experience?

- **3.1** What are the effects of providing children opportunities for exploration in AR serious games?

In our study, we offered children different levels of exploration in terms of task choices. Based on our research findings, we proposed the design guideline:

Design Guideline 7. Moderating the degree of exploration.

According to the work related to SDT, the integration of free exploration has the potential to enhance motivation. However, as shown in Chapter 6, a high level of free exploration (free choice) did not always result in a better learning experience. The degree of exploration should be moderated to avoid imposing an extra load on children since AR environments might already overload children with a large amount of information and complex tasks. Apparently, when children were presented with all the digital content at once, it hindered their effectiveness especially in the beginning when they were not familiar with the game. We suggest that AR designers always start the game from a simple option (by providing only a few options) and then gradually unlocking more options after children get familiar with the game. In addition, the game could also provide a more explicit visual guidance to assist children in their exploration, such as the direction to the next point, the difficulty of the exercises and so on, so that children can select their path easier.

– **3.2** What are the effects of providing children elements of fantasy in AR serious games?

In our research, we involved children in a fantasy world by providing them the game story. Based on the research findings, we proposed the last design guideline:

Design Guideline 8. Integrating the game story into the physical object.

Our study found that introducing elements of fantasy (a game story) resulted in higher perceived competence and relatedness than without a game story, but there was no significant effect on perceived autonomy and enjoyment level, nor on the task performance. Seeing the visual content might already stimulate the feeling of autonomy, whereas a game story helps stimulate the feeling of competence in terms of accomplishing a challenge and being connected with the game. Besides, in our game, we attempted to match the type of exercises children received when they stood on a certain point (e.g., ruins) in the digital game with the type of exercises under that point on the physical book, so that children would know which corresponding exercises they would get and choose the exercises they wanted to answer autonomously. However, during the experiment, we found that children did not pay much attention to the content on the physical book page but focused more on the ruins they wanted to save first. To better utilize the advantages of AR, we suggest that AR designers integrate the virtual game story into the physical books to bridge the gap between the AR world and the instructional materials, such as to augment and add fantasy to the traditional textbook children use daily. The textbook could be extended and changed to different stories and themes. Additionally, the game story could become topics to discuss among children. For example, they could decorate the classroom based on the theme in the book, which makes the game experience more immersive and motivating.

In addition, the interaction effect showed that when there was a game story, children who had to follow the system-order enjoyed the AR experience more than those who were offered a high level of free choices. While the enjoyment level was lowest when there was no game story and participants had to complete the exercises offered by the system one by one. Hence, to provide a better overall experience, the degree of free exploration and the elements of fantasy should be taken into consideration together, allowing children to make sense of their actions and consequences.

7.4.2 Reflection on the State of the Art AR Serious Games

This research project started in 2016, and some of the initial assumptions at the beginning of this thesis reflect the state of the art at that time. While we contend that these assumptions and the results still hold currently and in the (near) future, the development and research on AR serious games is in flux and new studies have been performed since. What do our findings mean in the context of more state of the art research? We will make a reflection for each research question.

Reflection on Research Question 1

In our competence study in Chapter 4, we applied the screen-touch interaction with a joystick, touches, and digital buttons. Quite a few AR games have released since the competence study, but screen-touch interaction is still widely applied. For example, Hassan, Rahim, & Shin (2021) presented an AR game for children to interact with digital cars with a mobile joystick appearing on the screen canvas to complete the learning tasks. Tuli and Mantri (2021) designed and developed a mobile-based AR learning environment for children to learn English with screen-touch interaction. Whenever children touched the screen, the animation of the 3D model would be triggered (Tuli and Mantri, 2021). In the study of Palamar et al. (2021), the AR books were designed with buttons on the screen canvas.

On the other hand, it is important to design more natural user interactions in AR serious games (Laine, 2018). The latest development of AR technologies is also changing the ways how users interact with AR content (Iqbal, Mangina, & Cmpbell, 2021). The developments in AR SDKs and APIs have provided increasingly more interactive capabilities for AR experiences, including a natural interaction with learning objects, gesture interactions, hand interactions, tangible interactions, and multi-modal interactions (Iqbal, Mangina, & Cmpbell, 2021). For example, multiple studies applied Leap Motion[20] for gesture interactions to offer children more vivid information (e.g., Al-Khalifa, 2017; Daineko et al., 2019; Sun et al., 2019) and for hand interactions (Cai, Tu, & He, 2018; Umeda et al., 2017; Yusof et al., 2020); some utilized Kinect[21] for full body tracking (e.g., Cai et al., 2017; Kourakli et al., 2017; Yukselturk, Altıok, & Başer, 2018); Hololens[22] has also been applied for gesture recognition (e.g., Hanna et al., 2018; Moro et al., 2021).

However, although these types of interactions have the potential to create a more interactive play environment and lead to higher motivation, Iqbal, Mangina, & Cmpbell (2021) have also identified that these devices are still expensive and dependent on the desktop PC network connection. The technologies and devices that are used for AR depend greatly on what is currently available on the market (Weerasinghe et al., 2019). Besides, children might face more difficulties in interacting with these new methods and require additional guidance, and the recognition rate of these devices should be improved in the future (Cai et al., 2017; Sun et al., 2019).

The design of our tangible interaction in Chapter 4 enables children to interact with the digital content naturally with current available mobile devices. In the

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[20] **Leap Motion** is a hand tracking module that captures the hands movements: https://www.ultraleap.com/product/leap-motion-controller/

[21] **Kinect** is a motion sensing input devices produced by Microsoft: https://developer.microsoft.com/en-us/windows/kinect/

[22] **HoloLens** is a pair of mixed reality smartglasses produced by Microsoft: https://www.microsoft.com/en-us/hololens

meantime, it also has the potential to be extended with new technologies, such as AR glasses or hand tracking devices, to make the interactions richer.

In our competence study in Chapter 4, the motivational effect of diegetic feedback with 3D models and animations has been confirmed. According to the latest studies, the visual richness, animations, and 3D objects are factors that could trigger higher perception of engagement for children (Conley et al., 2020; Gün and Atasoy, 2017; López-Faican and Jaen, 2020). López-Faican and Jaen (2020) also suggested that additional features and information could be incorporated with the 3D objects in the AR space to make the game more dynamic and appealing, which might trigger intrinsic motivation. In our case, we designed for explicit visual changes with 3D objects and animations to represent the completion of the exercises.

However, many latest developments of AR serious games still applied feedback mechanics such as scores and progress bars (e.g., Pombo et al., 2017). This might be due to the difficulties in generating 3D content. According to Scavarelli, Arya, & Teather (2021), there is a technological barrier for implementing AR into classrooms easily, since many resources are required to build 3D models and content.

In our research, we decoupled the learning content with the game content so that we could reuse the 3D models both during gameplay and to provide feedback information. The 3D progress map is an example of creating an immersive game environment that uses existing game elements to provide diegetic feedback. The idea can be extended with different resources and environmental conditions. The new AR technologies and devices mentioned above can also be used to generate diegetic feedback. For example, using HoloLens to place digital 3D animals in the real-world environment (e.g., classrooms), using Kinect or Leap Motion to interact with the animals based on gesture input, etc.

Reflection on Research Question 2

Since the start of this research project, more recent studies have identified that collaborative activities should be promoted in AR serious games (e.g., Garzón et al., 2020). Except for some cases where students were assigned into groups but used one digital device to visualize the AR content (e.g., Chang and Hwang, 2018), an increasing number of studies have focused on the synchronous multiplayer feature in the development of AR technologies. For example, Bhattacharyya et al. (2019) explored the development of a two-player mobile AR game using AR Core[23]. Nguyen (2020) developed a multiplayer (up to 4 players) AR board game using AR Foundation[24]. Plecher, Ludl, & Klinker (2020) designed an AR-escape-room with cooperative and competitive mode for up to 4 players with devices connected to the same server. Swearingen and Swearingen (2021) presented a cooperative AR game with the Photon network in Unity to provide face-to-face interactions for two players. Our design in Chapter 5 also allowed children to experience a synchronous AR game on mobile devices for two players, and MathBuilder allowed for more than two players. We could further investigate on the proper number of players, and compare AR Core, AR Foundation, or AR Kit[25], to create an optimized social experience.

The results of previous studies on social interactions in AR settings were inconclusive. For example, Ortiz et al. (2018) designed a competitive multiplayer game for a classroom activity with devices connected to the same network and was played by elementary school children turn by turn in the classroom. The result of the study showed that the multiplayer game allowed children to learn the educational content in a fun way, while the authors proposed to include the possibility of choosing between collaborative and competitive games in the future (Ortiz et al., 2018). Gün and Atasoy (2017) identified that students had different opinions towards individual and collaborating tasks, as some preferred to work individually while others preferred to work in groups. Conley et al. (2020)

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[23] **AR Core** is Google Play Service for AR: https://developers.google.com/ar

[24] **AR Founndation** is a cross-platform framework that allows developers to build AR experiences released by Unity Technologies :
https://docs.unity3d.com/Packages/com.unity.xr.arfoundation@4.1/manual/index.html

[25] **AR Kit** is Apple’s AR platform: https://developer.apple.com/augmented-reality/arkit/

suggested taking many factors into consideration when designing social communications for AR, such as the number of group members, roles and responsibilities, and the types of communication. López-Faican and Jaen (2020) addressed the essential role of face-to-face interactions between the players in educational games, which might allow children to practice social and emotional skills. Until now, the research in synchronous multiplayer AR games, especially for educational purposes, is still new and needs to be further explored. In our research, we aimed to amplify the advantages of social interactions in AR games with a collaborative mode or a competitive mode. We identified the advantages of collaboration and competition under different conditions and proposed the design guidelines with empirical findings.

Reflection on Research Question 3

Providing the free choice and direct feedback could support the feeling of autonomy in learning (Buchner and Zumbach, 2018). In Chapter 6, we explored the effects of providing self-directed choice and using game story to offer direct feedback.

The self-directed learning, which allows students to engage in the game at their own pace, is one of the core competences in the 21st century to support lifelong learning in the future (Hsu, 2017). Hsu (2017) compared the self-directed approach (students were free to choose any target to scan with at their own pace) and the task-based approach (students were guided by the system and had to complete the tasks one by one until all the challenges had been completed) in an AR educational game with the same learning goal. The results of Hsu (2017)'s study showed that the students who learned with the self-directed approach experienced a higher flow state. In Chapter 6, we designed two different ways to show the tasks as well: to display the digital exercises at once, allowing students to choose which one to answer freely, and to display the exercises one by one with a system-directed order. Our results differ from Hsu's study in that we could not find evidence that free choice in tasks led to increased enjoyment, or even increased feelings of autonomy. We did however find that the correctness rate was significantly higher when the exercises were shown with system-directed order than the self-directed way.

The results of our study might be influenced by the game story element of recovering a ruined village by answering the exercises. Students tended to pay more attention to the 3D buildings they wanted to recover and ignore the types of math exercises they would like to answer. We found that when there was a game story, the system-directed tasks were perceived as providing a higher feeling of competence. When there was no game story, the system-directed tasks were perceived as providing a lower feeling of competence.

Task structure and game mechanics could determine how the AR system and digital device are used by students (Alakärppä et al., 2017). Many game mechanics can be integrated into AR serious games, though it is challenging to keep children focused on the content more than the digital devices with added high interactivity (Wang, Lee, & Ju, 2019). Wang, Lee, & Ju (2019) examined the effects of AR books on children's interest and concentration on the book, and found that AR books decreased children's reading concentration significantly. An AR experience can become visually overwhelming (Endsley et al., 2017). However, Erbas and Demirer (2019) found that, if the AR application focused only on the demonstration of content, it did not have much motivating effect on children. Our design in Chapter 6 focused on balancing the motivating aspects of the AR game with a fantasy story and reducing the distraction with a system-directed task order.

In addition, the combination of physical and digital content, as the students could control which tangible objects to scan with, might also help them experience the flow state (e.g., Hsu, 2017). The 3D map in Chapter 4 and the set of toolkits in MathBuilder in Chapter 5 could be included to improve the self-directed learning experience.

7.4.3 Reflection on the Methodology

In addition to the implementation of the AR prototypes and the answers to the research questions, we also took a look back at the methodology we used to collect quantitative and qualitative data with children in our user studies, to shed light on the methodology to collect reliable opinions from young children.

Quantitative Data

In the first user study in Chapter 3, we applied a 5-point Smileyometer scale to collect opinions from children about the base game. As a result, our base game prototype received extremely high scores, since young children tended to rate extremely positive with Smileyometer scale with little granularity. In the same study, we also applied a PENS questionnaire to measure children's perceived competence, relatedness, and autonomy, with a 7-point Likert scale. Similarly, children also rated the game highly with PENS. To avoid the same result and to assist young children in selecting more nuanced answers, we developed an animated scale that used the animated cartoon characters available from iOS in our second study in Chapter 4. The animated scale was more colorful and visually expressive with different genders, races, and appearances, and their facial expressions and movements were recorded by the acting of two actors in real life. We conducted a pilot study with the animated scale and applied it with the PENS questionnaire to collect quantitative data from children again. Although the animated scale successfully attracted children in answering the questions, we received criticism during peer review for using an unvalidated scale and suggestions to apply more qualitative methods with children. Hence, in our third study in Chapter 5, we applied a one-item scale, IoCiS, and looked deeper into the interviews and observations. As a conclusion of the entire research, we decided to apply the PENS scale in our last study. Learning from the experience from previous studies, we explained each item one by one to the participants to avoid misunderstandings.

In addition to the motivational effect, how AR games would influence children's learning outcomes also matters. In the study of our base game, we evaluated the correctness rate between doing exercises in the AR game and on paper and found no significant difference. In our second study, we did not measure the learning performance for several reasons. Firstly, the exercises we used were simple calculations and learning gains would be minimal. Secondly, the study was short-term, and it would be difficult to notice significant improvements. In the third study, we applied a self-rated scale as the primary indicator of children's maths skills, aiming to find out the relation between their self-awareness and their behaviors in the AR game. According to our study results, children rated their maths skills relatively consistently and there was no significant correlation between the self-rated maths skills and the perceived relatedness. We also recorded the time they spent in different modes. The time they spent in different modes was significantly different. In our last study, we conducted a knowledge pre-test (on paper exercises) to see if participants were distributed equally across different conditions, and a post-test (in-game exercises) to measure children's task performance in terms of correctness rate by checking their play logs recorded by a screen-recording app.

To conclude, it is challenging to collect reliable quantitative data from young children in user studies. Our research explored different paths in evaluating children's experiences empirically. Based on our experience, we suggest that careful consideration should be taken in helping children understand the questions (explaining the meaning in front of them), the scales (conducting a pilot study to see if they can distinguish from different options), and the purpose of the study (letting them know that they are free to express their true opinions and it is not wrong to report negatively). In addition, as a learning game, we suggest looking for more objective measurements of children's academic skills, especially when they come from different schools or grades. Regarding the task performance, recording the game logs not only allows us to know how different modes may influence children's task performance, but also the reasons why they perform differently (e.g., clicking the wrong button due to a usability issue).

Qualitative Data

In our research, we conducted interviews to delve deeper into the results from questionnaires, and we observed children's behaviors by using observation forms. We suggest always applying this type of qualitative data when conducting experiments with children, offering children opportunities to further explain the reasons behind their behaviors and thoughts, and finding out more inspirations. For example, we were inspired by the observation results in the first study that children tried to move their book pages to interact with the virtual animals, which led to the tangible interaction in our second study. We put the elements of buildings and human characters into our last prototype since children expressed their need for this several times during interviews. We also came up with the idea of a diegetic 3D progress map since children said that they did not want the animals to disappear after they answered the exercises. Moreover, during the participatory design sessions, we also gave participants enough space to explain the design of their low-tech prototypes, which helped us understand the needs of children and think from children's perspectives.

7.5 Limitations and Options for Future Work

We mentioned limitations in each chapter before. In this section, we conclude the main limitations and provide options for our future research.

- Measurements

As mentioned above, we kept looking for a method to collect valid feedback from children in our research. Although the different perspectives of the various studies justified using different empirical evaluation methods, because of this, we were unable to systematically quantify the efficacy of different interventions. Therefore, a more systematic approach with a single evaluation method could be an interesting avenue for future research. Besides, the animated scale we developed has the potential to positively assist young children in focusing on answering questionnaires. In the future, a larger scale study could be carried out to validate the modified scale.

In our research, we applied an SDT-based scale, PENS, to measure psychological needs. To use the PENS scale, we signed a non-disclosure and limited use agreement with the company Immersyve[26], meaning that we can not publish the entire scale. Lately a couple of new scales have been developed that incorporate elements of PENS, such as the Player Experience Inventory (PXI) that measures player experiences, with a specific focus on allowing game user researchers to understand how game design choices are perceived by players, and how these contribute to psychological experience (Abeele *et al.*, 2020). In the future, the freely available scales may offer us more choices to measure the fun experience.

- Learning Outcomes

Our research aims to find design guidelines for designing motivating AR serious games for children. As a result, we focused less on the learning outcomes. The mathematics content in the AR prototypes were limited to simple exercises with no underlying instructional design methodologies or scaffolding principles and detached from a broader curriculum that could all intersect with the motivational considerations. It would be interesting to include more abstract or new knowledge and concepts to children and let them do the exercises to examine the effectiveness of the learning as indicated by the learning outcomes with different versions of the game. Future studies can also look for more objective measurements of children's academic performance, which could offer a deeper understanding of how the AR game could influence the learning outcomes. A long-term study might be another option.

[26] https://immersyve.com/

- Design Guidelines

Differences exist between our findings and findings in previous work of design guidelines for AR serious games. For example, in the study of Boletsis and McCallum (2017), the use of feedback mechanics, such as points and rewards, motivated players strongly in AR serious games, while we suggest that AR designers replace this kind of feedback with diegetic feedback that utilizes AR affordance better. When designing for social interactions, previous work suggested considering to either force, forbid or allow/neglect competition or teamwork (Ardito *et al.*, 2010). The game elements of competition could improve motivation significantly (Boletsis and McCallum, 2017). While we suggest that AR designers encourage collaboration more for motivation but use real-time competition to improve learning efficiency. Ardito *et al.* (2010) and Ko *et al.* (2013) proposed to minimize the interaction with the game tools and the physical effort, while we suggest that designers apply tangible interaction as an alternative solution and encourage children to interact with the physical objects such as textbooks, maps, and other physical objects. In the future, it would be interesting to compare our design guidelines with others. We could test if these design guidelines also work for different learning context as well.

There are other ways to satisfy the perceived competence, relatedness, and autonomy. In the future, we could add categories in the PLEX framework that we did not look at but could still be very interesting to lead to new game design guidelines, like discovery, expression, humor, sympathy, and thrill.

- Decoupled Learning Content

In our study, we purposely decoupled the conceptual knowledge construction with the game mechanics so that these motivation implications can be easily generalized to AR games with different learning subjects. In the future, we could change the maths subject to language learning, history, etc., to find out if the designed AR serious games would result in similar learning motivation for children. Another future direction is to integrate the learning content more within the AR game elements. The game would be a better learning tool if the learning goals in an educational game are attained through activities that are intrinsic to the game play (Camps-Ortueta *et al.*, 2019). How to integrate learning content more authentically and effectively in AR serious game is worth scrutinizing. For instances, the results of our study show that the element of game stories, which were not related to the maths knowledge, did not impact the overall enjoyment level and the learning performance significantly. While integrating the learning content into gamified stories and narratives could improve the learning motivation and reinforce learning objectives (Dunleavy, 2014). What's more, we suggest that AR designers apply diegetic feedback, while progressive feedback that reflects the "learned" and the "to be learned" is also very important in educational settings (Deen and Schouten, 2010). We can also look deeper into different playing styles and learning styles. Differences in different players, such as cultural differences, personality, and general demographics such as age and gender, may lead to different playing styles and preferences (Yannakakis, *et al.*, 2013), which can lead to different learning styles (Deen, 2015).

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CV

Jingya Li was born on the 17th of December, 1989, in Beijing, China. In 2012, she received her Bachelor Degree in Software Engineering at Beijing Jiao Tong University, China. In 2016, she received two Master Degrees in Computer Technology at Peking University, China and in Technical Communication at University of Twente, the Netherlands.

In September 2016, she started her PhD research in the Department of Industrial Design at Endhoven University of Technology, the Netherlands. Her PhD was carried out under the supervision of dr. Jun Hu, prof.dr.ir. L.M.G. Feijs, and dr. E.D. van der Spek. This thesis is the result of her PhD research on the topic of "Design Guidelines for Augmented Reality Serious Games for Children".

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