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Extracting Design Guidelines for Augmented Reality Serious Games for Children

JINGYA LI[1], ERIK VAN DER SPEK[2], JUN HU[2], AND LOE FEIJS[2]
[1]School of Architecture and Design, Beijing Jiaotong University, Beijing 100044, China
[2]Industrial Design (ID), Eindhoven University of Technology, 5612 AZ Eindhoven, The Netherlands

Corresponding author: Jingya Li (lijy1@bjtu.edu.cn)

ABSTRACT Augmented Reality serious games have become an emerging solution to positively influence the learning experience for children born in the digital age. However, systematic and empirically tested design guidelines for AR serious games remain largely unexplored. In this study, we investigated the design guidelines by designing and developing four AR serious games with different mechanics inspired by the psychological needs within Self-determination Theory, following with four user studies respectively. In the first study, we explored the AR game concepts by conducting participatory design sessions. In the second study, we investigated how children react to different types of interactions and feedback mechanics in AR serious games with 32 participants. Then, we scrutinized the effect of social interactions in AR serious games on children with 24 participants. Lastly, we designed an AR game with four different versions, tested pathways to immerse children to explore and play in an AR fantasy world with 81 participants. Generally, this research explored the concepts, prototypes, and results of incorporating AR with serious games for children. We realized multiple AR prototypes inspired by SDT and generalized a set of design guidelines, which are intended to help future related designs in AR serious games.

INDEX TERMS Augmented reality, elementary education, serious games, design guidelines.

I. INTRODUCTION

Today's children are born in a world with the rapid growth of multimedia technologies. Since it is already an important part of their life, it is an opportunity here to better utilize the technologies to facilitate education. The high level of motivation and engagement with multimedia technologies has the potential to enhance the learning experience [1]–[3]. Consequently, digital games focusing on educational purposes, often referred as serious games or game-based learning [4], have become an increasingly important method in learning [5]–[7].

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 [7], [8]. However, empirical evidence for serious games to be more motivating in general than conventional instruction might be lacking [7]. Serious games can be a supporting factor in the learning process, but might not be more motivating than textbooks [9]. 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 [10].

In the 21st century environment, including traditional textbooks in elementary school has still shown significant positive effects in students' learning achievement [11]. In the meantime, teachers increasingly rely on digital instructional materials at school, suggesting that school textbooks need to be connected with technology too [12]. The traditional and digital instructional materials have shown different advantages in terms of academic effect, where the best textbook presentation of the future should combine both tangible paper identity and digital components [13]. However, in the current school environments, it is not easy to implement a strategy to involve both paper and digital media [13]. 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 [14], 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 [14]–[18].

Augmented reality (AR) technology, which enables the user to see the real world with virtual objects on top of it [19], has the potential to solve these problems. Integrating AR

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with games could take the advantages of serious games and traditional learning materials, providing benefits of unique visualization and interaction possibilities [20], supporting social interaction [21], [22], as well as maintaining high levels of motivation and influencing children's learning experience positively [6], [23], [24]. The increased motivation and active engagement in AR games have the potentials to be translated to compelling educational media and make learning more immersive and enjoyable for children [25].

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. While previous studies have applied game-design mechanics to learning processes in the design of serious games, a similar systematic and empirically tested approach towards the design of AR-based learning is still missing [26]. Existing guidelines developed for non-AR settings are likely to have limited applicability to AR [27]. The question of how one should design an AR serious game to stimulate learning motivation therefore remains unanswered and requires further exploration [28]. 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 [29].

In this paper, we focus on articulating our design process and extracting design guidelines for AR serious games based on our four studies. This paper does not focus on the detailed outcomes of each research phase but on how we translated theoretical principles (Self-determination Theory) into the design of AR serious games for elementary school children, and how the outcomes of each phase affected the design decisions in the overall process.

II. BACKGROUND

A. MOTIVATION IN AR SERIOUS GAMES

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 [25], [30]. AR serious games have been reported as motivating and engaging for children in their learning experience, stimulating positive learning attitude [31], [32]. 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 [33]. For example, [34] conducted a user study with an AR-based mobile system and a conventional inquiry-based mobile learning approach for conducting natural science inquiry-based learning activities for children. Their study indicated that the AR system could lead to significant higher motivation. Similarly, [35] proposed an AR-based learning game for reading comprehension activities for children and found that children displayed greater motivation and interest in the activities with the AR game than the traditional approach. In the study of [36], AR-based digital learning game was integrated in a marine education program for children. According to their study, the AR game provided greater motivation and raised the level of children's engagement than conventional marine learning program. Applying AR book as an alternative material for children learning new concepts such as bacteria, [37] reported that children preferred the AR book to other learning materials like 2D graphics and 3D physical objects. [38] examined the effect of an AR pop-up book for elementary school language learning and found that 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. [39] presented an AR system for an across-spaces learning activity for children. The study showed that AR not only enhanced children's learning engagement and motivation but also helped them achieve their learning objectives. AR-SEE [40] was a mobile phone-based AR system for passive solar energy education. According to the study, despite AR serious games might reduce usability and increase task completion time compared to the desktop version, they could enhance participants' learning motivation.

B. DESIGN GUIDELINES OF AR SERIOUS GAMES

Among the studies of the design of AR in the education domain, several studies also produced design guidelines. For example, [41] introduced four AR case studies, 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, and physical interaction in AR applications. [42] 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, [43] discussed the process for design guidelines of location-based mobile games for learning through analyzing existing papers and defining guidelines into five categories. Another study [44] 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, [29] reviewed literature and revealed three design principles when designing AR serious experiences. [26] proposed a research methodology to apply game design patterns to AR-based learning games for the training of professional education based on previous studies. 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 [26].

Overall, although 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

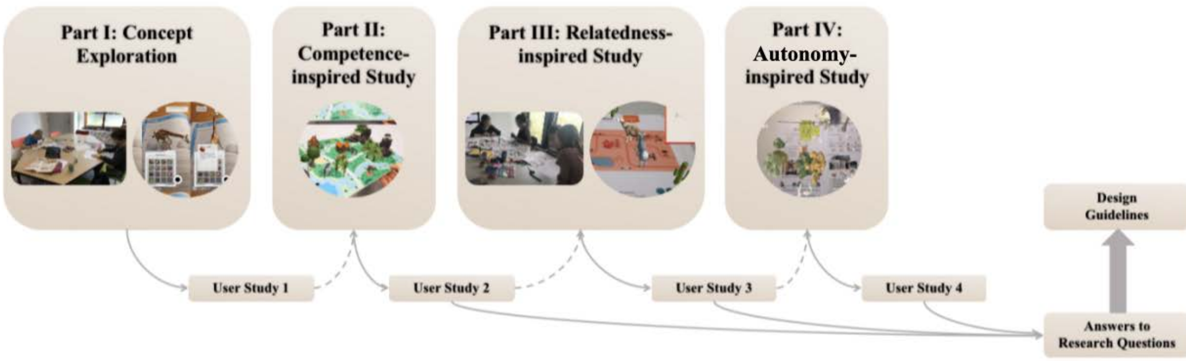

FIGURE 1. **Research phases.**

for elementary school children, is still lacking. It is necessary to conduct research that focuses on systematically tested guidelines for AR serious games.

C. THEORETICAL BACKGROUND

In this research, we applied Self-determination Theory (SDT), which is a well-established theoretical framework for intrinsic motivation research in digital games and has been used to study the motivational appeal of digital games [45]–[47], inform gameful design [48], [49], and evaluate the playful experience [50]. Intrinsic motivation is defined as "doing something because it is inherently interesting or enjoyable" [51] (pp.55), leading to enhanced creativity and improved learning outcomes [51]–[53].

SDT includes three basic psychological needs, including the need for competence, the need for relatedness, and the need for autonomy, which are proven to be positively associated with intrinsic motivation and independently predict a higher enjoyment level [46], [47], [51], [52], [54], [55]. Evidence has shown that the three psychological needs of human motivation also fit well in an educational environment [56]. However, how to translate design knowledge on how to apply SDT principles in the design of AR-specific serious games was still new. We hope that our research can contribute to that body of knowledge. To address our research goal, 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?

III. RESEARCH PHASES

This study includes four phases. In the first phase, we explored and evaluated the AR game concepts; in the second phase, we continued to develop the basic concepts with AR specific game design principles; in the third study, we scrutinized the effect of social interactions within the AR serious game on children; and in the last phase, we tested pathways to immerse children to explore and play in an AR fantasy world. Fig. 1 shows the overall research phases of this study.

A. PHASE I: CONCEPT EXPLORATION

1) CONCEPT DESIGN

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 [57], we applied the participatory design method with two elementary school children aged 7. We chose mathematics as the learning subject since that learning motivation and interests are suggested playing an important role in children's mathematics performance at school [58]–[60]. During the early elementary school years, a high level of mathematics-related motivation would further contribute positively to children's learning performance [61]. Fig. 2 shows the process and the results of the participatory design, where children expressed their thoughts and shared their ideas on how to translate mathematics exercises from their textbook into an AR game.

Based on the ideas collected from the participatory design session, we developed the first version of the AR game with basic functions: there are animals in the textbook waiting for children's help to solve maths problems. Then, children start to scan the textbook and find animals. When an animal shows up, children can interact with the animal by touch-input. They can control animals to move around with the joystick. Children can choose some of them to feed the animals, and an exercise interface will appear and children can write their answer to the displayed exercise. Upon completion, children will get immediate feedback showing right or wrong answered questions accompanied by either a gift from the animal, or an encouraging message for them to keep going.

Before we could fill in the AR game with more features, we first conducted an experiment to see if the current game concepts would be accepted by children. Two user studies have been done in two different countries [96].

2) USER STUDY

In China, 20 participants (10 Males and 10 Females; M = 8.2 years, SD = 0.62 years) were randomly assigned into two equal groups. We used a within-subject design for the study, where each group experienced the AR game and the paper exercise in different orders. All participants individually performed 10 mathematics exercises each time with roughly the same difficulty level, on paper or AR game and

FIGURE 2. Process and results of participatory design.

vice versa. The exercises were chosen and modified from the math textbook of grade 3 by the teacher. The paper exercises contained the images of same animals as the AR game, so that purely the interactive AR aspects were tested instead of the fantasy narrative of anthropomorphic animals. After the paper and the AR game, participants were asked to complete a questionnaire using items from Intrinsic Motivation Inventory (IMI) [62]. At the end of the study, participants were interviewed regarding their preference between the paper exercise and the AR game.

In the Netherlands, 18 participants (10 Males and 8 Females; M = 7.1 years, SD = 0.32 years) took part in the user study. 18 participants were randomly divided into two groups. Same as the user study in China, each group experienced the AR game and the paper exercise in different orders. After both paper and the AR game, participants were asked to complete the questionnaire and were interviewed.

3) RESULTS

The results of the study indicated that in general, the AR game prototype achieved significantly higher ratings on the overall experience over the paper version. The AR game concept with animals walking over ones' textbook could be accepted by both children from the two cultures to do mathematics schoolwork. No significant difference was found in the in-game learning performance between the AR game and the paper version.

From the interview 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" and "richer reactions from the animals". During the study, it was also observed that children tended to share 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.

This study is the first step in our research, proving the positive motivating effects of the working prototype of the AR game for children. It came as a surprise to us that how much the children liked the AR version. To our estimation, the base game lacked a lot of engaging game mechanics and design features stimulating competence, autonomy, and relatedness. 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 based on SDT. 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, augmenting the basic game idea to include game mechanics to stimulate feelings of autonomy, competence, and relatedness. In the next part, the application of this method continues with the design of a competence-inspired AR serious game.

B. PHASE II: COMPETENCE-INSPIRED STUDY

1) CONCEPT DESIGN

Competence refers to the individual's sense of self-efficacy, which describes an individual's belief in being able to successfully overcome challenges [63] and success while interacting with the environment [64], [65]. In our research, we aimed to explore which types of AR-specific challenges should we offer to children, and which types of feedback should we provide. We formulated the first sub research question:

RQ1. How to incorporate AR-specific elements in serious games in terms of different types of challenges and feedback mechanics?

To answer RQ1, we presented a set of AR game prototypes and elucidated the design decisions based on participatory design sessions and previous user study [96]. Similar as in the base game, when children scan the physical book, a virtual animal and different food carrying answers on top of them will show up. The goal of the current game is to navigate the animal to eat the food carrying the correct answer for the maths exercise.

a: CHALLENGE

In AR environment, the interaction between the user and the AR application could be challenging and is one of the main things to consider when developing AR for education [66]. In AR environments, users can complete the challenges

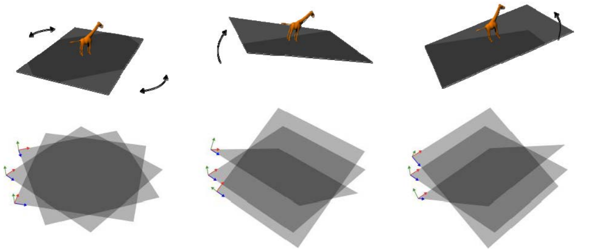

FIGURE 3. Reactions of the virtual animals according to different actions: turning, speeding up, slowing down.

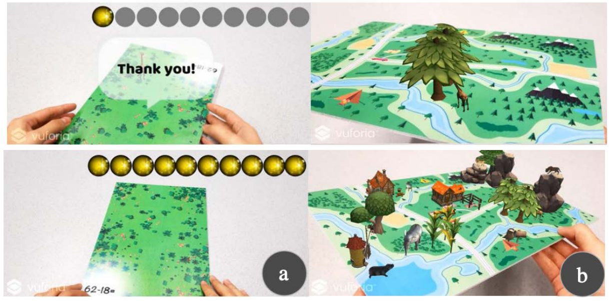

FIGURE 4. Different feedback mechanics: left: progress bar; right: progress map.

using different interaction techniques [67]. In the base game, we applied the screen-touch interaction, which is a common interaction technique used in AR games for children (e.g., [35]), allowing them to select which item they wish to act upon by touching on the digital screen of the mobile device with fingers [67]. In our base game, we found that children had no difficulty in completing the challenges with screen-touch interaction. Therefore, in this version, children could also guide the animals to eat the food by touching on top of the food on the screen.

In the meantime, it is suggested that AR interaction should be appropriately designed and created to support seamless interaction between the virtual and physical world [68]–[70]. Tangible interaction has the potential to offer a more entertaining experience to users with a series of intuitive and natural interactions [71], [72]. Hence, we explored how to complete the challenges with tangible interaction in the AR game. We turned the physical book itself into the interface with which to control the game by calculating the change of the angles between the AR camera and the physical interface and mapped it onto the animals in the 3D coordinate system in real-time. Children need to rotate the book to turn the animal and tilt the book to make the animals move. See Fig. 3.

b: FEEDBACK

According to [73], feedback is one of the essential game design mechanics that can evoke feelings of competence. In previous studies, 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 [74], [75]. In our base game, we also applied the traditional progress bar: children would see their performance immediately after the animal eats the food. We transferred the 2D progress bar into the new game and designed it to show the progress in a more explicit way: children could see 10 golden circles if they find all the correct answers (Fig. 4 left).

However, the 2D progress bar includes simple game objects that could be spawned in any digital game, and therefore does not capitalize on the more unique AR affordance of a mixed reality game world. Therefore, we introduced an interactive progress map in the new game: after the animal eats the correct food, children could see the same animal appear on an extra physical map as the completion of the exercise. They could move the the map to view the animals from different angles in the real-world perspective (Fig. 4 right).

2) USER STUDY

We conducted experiments to figure out how they reacted to these different interaction styles and feedback mechanics. A total of 32 children (16 Males and 16 Females) with the mean age of 7.72 were recruited in the Netherlands. We assigned children to different condition groups randomly and each child was exposed to two different types of interactions and answered the SDT-based questionnaire, IMI and Player Experience of Need Satisfaction (PENS) [46], [76], after each interaction in a counter-balanced manner.

3) RESULTS

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. The interview results showed differentiated reasons for possibly liking one over the other. Children preferred the screen-touch interaction because that it was easy to master and required less effort. While the tangible interaction required children to practice in order to grasp the precise and somewhat cumbersome controls of the 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 motivate children as they found it interesting and fun even though it required more effort.

Regarding the feedback mechanics, our results indicated that the 3D progress map was significantly preferable over the 2D 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

FIGURE 5. Process and results of participatory design.

following the game rules to completion. Intrinsic motivation does not increase solely due to higher feelings of competence unless it is also accompanied by an increased feeling of autonomy [53]. Even positive feedback may impede people's inherent need for autonomy and thus decrease their intrinsic motivation [77].

C. PHASE III: RELATEDNESS-INSPIRED STUDY

1) CONCEPT DESIGN

According to SDT, relatedness represents the basic desire of people interacting with the social environment [78]–[81]. The feeling of relatedness concerns the sense of belonging [79]–[81] which could be affected by teammates in the real world and in the digital game [64], [82].

To find inspirations for the concepts of the relatedness-supportive AR game, we conducted another participatory design session with eight participants (Fig. 5). Competition and collaboration were the ideas participants came up with for multiplayer games. Developed concepts included children 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. 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.

We formulated the second sub research question:

RQ2. How to amplify the advantages of social interactions in AR serious games in terms of competition and collaboration?

Based on the results from previous studies and the current participatory design session, we designed and developed the relatedness-supportive AR serious game [96]. 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 animals. 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. Based on the findings from our second study, in the current study, we kept applying the screen-touch interaction with a joystick to move the animals, and children could collect the animals and the animals would play a cheerful animation to provide immersive feedback.

a: COMPETITION MODE

Competition refers to the experience of competing against each other. 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 (Fig. 5 right).

b: 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.

2) USER STUDY

To understand different perceptions of children and different play patterns under different social contexts in the AR environment, we conducted a pilot study with four children and a formal user study with 24 elementary students (Mean age = 9.04, SD = 1.04, 8 Males, 16 Females) in the Netherlands. Participants were grouped in dyads and were presented with the two modes of the game in a counterbalanced order. Children were asked to rate their relationship with the other player in the group by using the Inclusion of Community in Self Scale (IoCiS) [83]. We also conducted interviews with each group and observed their behaviors during the game.

3) RESULTS

In general, we found that participants perceived significantly more relatedness with the collaboration mode than the competition mode in the AR game.

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.

Under 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. 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. Children would discuss together with each other under the collaboration game, sharing 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. 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.

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 between the time spent on each exercise in the competition mode and in the collaboration mode. 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.

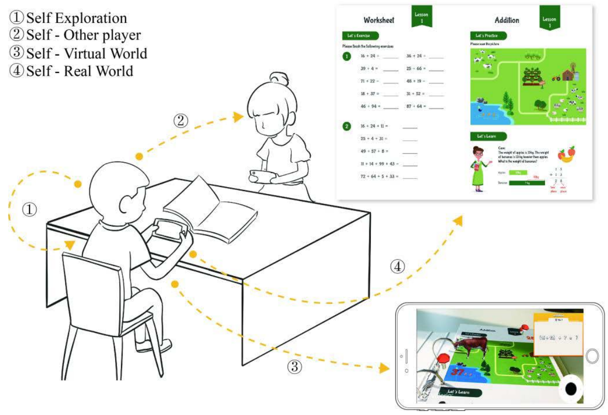

FIGURE 6. Four types of social interactions.

Fig. 6 shows a vision of four types of social interactions identified based on 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.

D. PHASE IV: AUTONOMY-INSPIRED STUDY

1) CONCEPT DESIGN

Autonomy within SDT is defined as a sense of volition or willingness when doing a task [46]. Methods to enhance autonomy include providing choice and informational feedback as reward and meaningful instruction [46], [73]. The provision for choice allows users to choose between several courses of action [47]. 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 [47], [73]. In addition, the choice provided should also lead to meaningful information. 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 [64]. Therefore, in our study, we integrated task choice and game story into the AR settings to investigate their effects on stimulating motivation.

We formulated the third sub research question:

RQ3. How to apply game design mechanics in AR serious games in terms of task choice and game story?

Game Story. A game story is one of the motivational tools to add sense to the learning task, giving the learning activity a specific form to be linked to the context [43]. The meta-analysis of [4] also showed that the game story had a positive effect on motivation. In the context of AR serious games, previous research also suggested driving the player interaction and learning through gamified stories or narratives [84], which could provide the structure and rationale for the AR experience and impact the quality of the experience profoundly [85], [86]. While the game story may have the potential to enhance motivation, research indicated that the fantasy game environment might lead to lower learning achievements [8]. [87] found no positive effect of the game story on learning performance.

In our previous studies, we found that the progress map triggered a higher enjoyment level. Children kept asking for more types of 3D elements such as buildings, places, and ''people'' walking in the game. Hence, in the current game, we designed human characters and a village with buildings and plants, and the village would be recovered from ruins to its original look by children answering the exercises correctly. Children received this kind of feedback to know if their answers were correct or not.

In the version with game story, when children scan the textbook, they start with a game story that a village has been destroyed. The game story will guide the children to help recover the village. Then children see the fantasy world popping up on top of the book page, full of ruins with luminous points. In the version with no game story, 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.

Task Choice. Offering task choice refers to providing choice among options and invitations to participants to self-direct their own tasks [88]. However, SDT research also highlights that autonomy should not be equated with the mere presence of choice [48]. In addition, to enhance the perceived autonomy, a game should be designed to respond dynamically to an individual's task choice without constraining them [46]. In parallel, too much choice may lead to cognitive overload during the experience, which is one of the most frequently reported AR design challenges [48], [85], [86]. 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 [89].

In the version with task choice, children see the AR world popping up on top of the book page. There are 10 luminous points and each of the ruins carries a maths exercise. Children can choose to answer the exercise or not. If the exercise is answered correctly, the ruin will recover to either a building, plants, etc. If the exercise is answered incorrectly, the point will stay the same and children can come back to answer the question again at any time. In the version with no task choice, children will finish the exercises following the system-directed order. They have to answer the first exercise correctly to unlock the next one. All the other elements remain the same.

2) USER STUDY

We received 81 available results from 42 boys and 37 girls (2 did not identify) aged 7-10 years old (Mean = 8.82, SD = 0.83). Participants took a knowledge pre-test with exercises similar to the exercises. Then they were randomly assigned to one of the 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. After completing of the game, participants answered the questionnaire with items selected from IMI and PENS. Lastly, participants were interviewed about their perception of the overall experience.

3) RESULTS

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. Besides, the fantasized game story did not negatively influence the learning task performance.

Regarding 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.

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.

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 following section we propose design guidelines to design AR serious games with the aid of SDT-inspired mechanics.

IV. DISCUSSION

In our research, we tried to translate SDT principles into the design of AR serious games by applying each psychological need to AR features, exploring the design space of AR serious games. We respond to the research questions with a set of design guidelines to help future related designs in AR serious games for elementary school children.

To answer RQ1, we specifically integrated different types of interactions and feedback mechanics for children and investigated the effects of them on children. Based on the research findings, we proposed three design guidelines:

Design Guideline 1. Mainly applying screen-touch interaction.

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.

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

It is important to design more natural user interactions in AR serious games [90]. The latest AR technologies have the potential to create a more interactive play environment but are expensive and dependent on the desktop PC network connection [91]. Children might face more difficulties in interacting with these new methods [92], [93]. The design of our tangible interaction enables children to interact with the digital content naturally with mobile devices. We 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 in our game is the textbook the animals are standing on top of. 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.

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

We suggest AR designers utilize the special affordances of AR to generate a mixed reality experience and create an immersive play space. 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 feedback. This kind of feedback could also 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.

To answer RQ2, we integrated collaboration and competition as social interactions in our games. Based on the research findings, we proposed three design guidelines:

Design Guideline 4. Encouraging collaboration.

As observed in our base game and the autonomy-inspired game, children would turn to others for help during the game and vice versa. Our relatedness-inspired study also enabled competition and collaboration interactions among children. As a result, we found that children felt more connected when they were collaborating. Consequently, we see strong potential to create a shared augmented space in the game for children to work together and communicate naturally. 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. 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 AR designers design for real-time competition, and that the results of the competition should be embedded in the 3D 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.

Design Guideline 6. Designing for appropriate social interactions.

When designing for social interactions in AR serious games, it is important to distinguish different context to generate the most appropriate experience for children. To be more specific, in the competition mode, 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, 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.

To answer RQ3, we offered children different levels of exploration in terms of task choices and involved children in a fantasy world by providing them the game story. Based on our research findings, we proposed two design guideline:

Design Guideline 7. Moderating the degree of choice.

The degree of choice 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 AR designers always start the game from a simple option 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 etc., so that children can select their path easier.

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

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. To better utilize the advantages of AR, we suggest 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.

V. CONCLUSION

In this research, we explored the design space for AR serious games based on SDT. We realized four AR serious games to improve the learning motivation and learning experience for elementary school children and generated eight design guidelines for future AR serious games for children. Differences exist between our findings and findings in previous work. For example, in the study of [94], the use of feedback mechanics, such as points and rewards, motivated players strongly in AR serious games, while we suggested AR designers replace this kind of feedback with 3D feedback. When designing for social interactions, previous work suggested considering to either force, forbid or allow/neglect competition or teamwork [43]. The game elements of competition could improve motivation significantly [94]. While we suggested AR designers encourage collaboration more for motivation but use real-time competition to improve learning efficiency. [43] and [95] proposed to minimize the interaction with the game tools and the physical effort, while we suggested 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. It would be interesting to compare our design guidelines with others in the future.

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JINGYA LI received the bachelor's degree in software engineering from Beijing Jiaotong University, China, in 2012, the master's degree in computer technology from Peking University, the master's degree in communication technology from the University of Twente, in 2016, and the Ph.D. degree in industrial design from the Eindhoven University of Technology, in 2021. She is currently working with the School of Architecture and Design, Beijing Jiaotong University. Her research interests include immersive technologies, data visualization, and serious games.

ERIK VAN DER SPEK received the master's degree in game technology and the Ph.D. degree in human–computer interaction from Utrecht University, in 2007 and 2011, respectively. He joined the Eindhoven University of Technology (TU/e), as an Assistant Professor. He is currently an Assistant Professor of game and play design. He is the Research Director of the TU/e Game/Play Laboratory and a Secretary of the International Federation for Information Processing (IFIP) Technical Committee on Entertainment Computing (TC14). He has been a Board Member of the TU/e Data Science Center and the Chair of the ID Department Council and Squad Leader of the Vital Play, Play and Learn and Games and Play squads. He is also with the Steering Committee and has been a Program Chair of ICEC. He has been the Student Game Competition Chair of CHI Play and ICEC.

JUN HU received the B.Sc. degree in mathematics, the M.Eng. degree in computer science, and the Ph.D. degree from the Department of Industrial Design, Eindhoven University of Technology (TU/e).

He is currently a Professional Doctorate in user–system interaction with the TU/e. He is a System Analyst and a Senior Programmer with the qualifications from the Ministry of Human Resources and Social Security and the Ministry of Industry and Information Technology of China. He is the Head of designed intelligence and an Associate Professor of design research on social computing with the Department of Industrial Design, TU/e. He is also a Distinguished Professor with the School of Digital Media, Jiangnan University. He has authored or coauthored over 180 peer-reviewed publications in conferences and journals in the field of HCI, industrial design, computer science, and design education. He is a Senior Member of ACM. From 2006 to 2007, he served as the Secretary-General for the Association of Chinese Scholars and Engineers, The Netherlands, where he was the Chairperson, from 2008 to 2009. He is also the Co-Chair of the Working Group Art and Entertainment of International Federation for Information Processing Technical Committee on Entertainment Computing (TC14). He is the Co-ordinator of the TU/e DESIS Laboratory in the Design for Social Innovation and Sustainability Network. He serves on the editorial boards for several international journals.

LOE FEIJS received the master's degree in electrical engineering and the Ph.D. degree in formal methods from the Eindhoven University of Technology (TU/e), in 1979 and 1990, respectively. After a stint as a Guest Researcher at the CSELT, Italy, he started working as a Software Developer at Philips Telecommunication Industry, on embedded systems for digital telephone exchanges. In 1984, he joined Philips Research, a position he held for 14 years. He took a position as a Professor at the TU/e, in 1994, initially with the Department of Mathematics and Computer Science and later with the Industrial Design Department. He worked as a Scientific Director of the Eindhoven Embedded Systems Institute. From 2001 to 2006, he was the Vice-Dean of the newly founded Department of Industrial Design. He was the Co-Founder of the DeSForM Conference. His team has set up and is participating in the H2020 Do Change Project. His algorithm-based designs are published in Leonardo and presented at DDW and the yearly Bridges Conference on Mathematical Art.