Turning Your Book into a Game: Improving Motivation through Tangible Interaction and Diegetic Feedback in an AR Mathematics Game for Children

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ABSTRACT
Augmented reality game-based learning has become an emerging trend in the field of education as it has the potential to increase children's learning motivation for subjects such as mathematics. However, to achieve the benefits for children effectively, AR serious games need to be appropriately designed, especially in respect to their novel interactions and representation paradigms. In this paper, we report on an exploratory experiment to investigate how different interaction techniques (digital screen-touch interaction vs real-world tangible interaction) and different feedback mechanisms (non-diegetic feedback vs diegetic feedback) affect 7-8-year-old children's motivation for mathematics learning. Our results show that diegetic feedback led to the game being considered significantly more enjoyable, as well as inducing greater feelings of competence and autonomy; screen-touch interaction versus tangible interaction did not change motivation directly, nor did we find interaction effects between the presentation and interaction modes. By analyzing the results and based on previous studies, we identify recommendations for designers to develop motivating serious AR games for children.

Author Keywords
Augmented reality; Game design; Motivation; Interaction techniques; Children.

CSS Concepts
• **Human-centered computing~Mixed / augmented reality**; *User studies; Empirical studies in HCI*; Empirical studies in interaction design;

INTRODUCTION
Augmented Reality (AR) game-based learning is gaining significant momentum in the education sector with the potential to improve the learning experience, especially for the new generation of children that has grown up playing with digital technologies and might find game-based learning more engaging than traditional learning approaches [3,18,19,35,38]. Children often experience mathematics as a difficult subject during primary school years [49], which makes the learning motivation and engagement an important factor in their mathematics performance [4]. Previous studies have noted significantly higher motivation with AR games over non-AR games [35]. 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 [18,35,54]. However, further systematic research needs to be carried out to identify how serious AR games should be designed in order to improve children's motivation [36]. 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 [30].

Figure 1. An AR mathematics game for children. Children will see the 3D animals on a paper map after they complete the math exercises.

Therefore, giving the relevance of this topic, this paper specifically focuses on exploring the motivational effect of different elements in AR games on children (Figure 1). By doing so, we aim to contribute empirical understandings that could support future AR game designers, and to explore the design space in terms of enhancing the play-and-learn experience. Specifically, we focus on investigating and comparing two common interaction techniques in AR environments: real-world tangible interaction (through children's manipulation of a physical textbook) and screen-touch interaction (through digital touchscreen). Besides, we explore two feedback mechanisms in AR games: non-diegetic feedback (where the feedback is delivered through a

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2D progress bar) and diegetic feedback (where the feedback is presented with additional 3D animations).

To explore these two interaction styles and two feedback mechanisms, we first review current studies on AR games related to their motivational effect. Then we present a set of AR game prototypes and elucidate the design decisions based on co-design sessions and previous user tests. These game prototypes share a commonality with general serious game design but differ in the mentioned interaction styles and feedback mechanisms. By comparing them through an experimental study, we can investigate the way children are motivated in the AR experience.

To conclude, we generalize our empirical findings and discuss them along previous related studies to propose recommendations aimed at helping designers in making appropriate design choices in AR to support the playful and enjoyable experience for children in the future.

RELATED WORK

Motivation in AR Learning Games

Motivation plays a critical role in designing effective educational applications for children [31]. 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 [30]. AR-based learning games have been reported as more motivating and engaging compared to traditional learning games for children in the learning experiences, stimulating their desire to learn, attracting their attention, and enhancing positive learning attitude. For example, Chiang et al. [11] proposed an AR-based mobile learning 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 conventional inquiry-based mobile learning approach. Hendrys et al. [23] 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 activity with the AR game than the traditional approach. Lu and Liu [29] integrated an AR-based digital learning game in a marine learning program for primary school children. According to their study, the AR game raised the level of engagement of children and provided greater motivation than conventional marine education programs. Hung et al. [26] examined the effect of applying AR as an alternative material to motivate children in learning about the bacteria. Results from their study showed that children preferred the AR book to other learning materials such as 2D graphics and 3D physical objects. Vate-U-Lan [53] reported on an AR pop-up book for primary school language learning. According to the study, the AR book improved the engagement in the learning activity and children indicated that the AR book was a stimulating educational resource that increased their desire to learn. Munoz-Cristobal et al. [32] presented an AR system for an across-spaces learning activity for primary school children. In their study, they found that AR helped children achieve the learning objectives and enhanced their learning engagement and motivation. Juan et al. [9] presented an AR learning 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.

Previous studies have shown that AR learning games have the potential to enhance children's motivation and improve their learning experience. However, there is a lack of systematic understanding on how to design these games. Children might lose interest when the novelty of the new technology wears off [18,28]. Starting from this perspective, we examine the novel interaction and representation paradigms that AR affords to better understand how they can influence children's learning experience and how to take advantage of the affordances and potentials of them effectively.

Interaction Types

One of the important features of AR is that it enables real-time interaction, combining the physical and virtual world [5]. The interaction between the user and the AR application is one of the main things to consider when developing AR for education [22]. However, previous studies on AR have mostly focused on displaying additional information on top of the real world without specifically concerning itself with how users would interact with the system [48].

In AR environments, users can interact with the game using different interaction techniques [38]. Screen-touch is one common interaction technique used in AR games for children (e.g., [10,23,28]), allowing them to select which item they wish to act upon by touching on the digital screen of the mobile device with fingers [38]. This kind of interaction is based on the virtual content, while it is suggested that AR interaction should be appropriately designed and created to support seamless interaction between the virtual and physical world [7,48,57]. 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 [57,58].

A number of previous studies have applied tangible interaction tools such as paddles and cubes with paper-based documents like books, aimed at making children enjoy more and perceive more fun (e.g., [24,51,55,58]). 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 [48]. Children would expect the virtual objects to react and behave analogously to the physical objects in the real world [25]. Consequently, tangible interaction tools may confuse children what it is in their actions that makes the system react

[25]. 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 [20]. In the study of Grasset et al. [20], they explored the design space for the interaction in a real book and gave an example that 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

Feedback Mechanisms

In traditional video games, players should be given appropriate and clear feedback at appropriate times during the game to keep them motivated at a high level [1,50]. Feedback lets players know where they are in the game process [2]. In learning games, feedback in games is even more important [2]. Observations from Bretagne et al. 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 gameplay [1]. Hence, feedback mechanisms on the player's 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 Bretagne et al., the player's progress in the game was represented by a series of symbols within a vertical bar [1]. This type of progress bar is non-diegetic element, which is not visible inside the spatial game space or the fictional game world [8]. Non-diegetic game elements take part in the game action and deliver feedback or relevant information to players, such as the health bars and the objective indication [13]. 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 et al., a 2D progress bar was presented on the digital screen providing game feedback to children [33]. 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.

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 [8]. Diegetic game elements are a part of the game world where players need to observe the environment in order to perceive the information [8]. For example, the in-game devices or objects, such as a watch or a diary, are frequently used to provide the player with feedback information [8].

AR technology is characterized by its 3D registration of the virtual and physical objects [5], which can be utilized to develop, in a sense, diegetic feedback in a mixed reality setting. However, the motivational effect compared to non-diegetic feedback remains unclear. Thus, in this study, we look into these questions between the two different feedback mechanisms

Self-determination Theory

Self-determination theory (SDT) is one of the most established theoretical frameworks for intrinsic motivation research in video games [15,17]. Intrinsic motivation is defined as "doing something because it is inherently interesting or enjoyable" [42], which results in improved learning outcomes and enhanced creativity [43]. Within SDT, there are three basic psychological and intrinsic needs, namely the need for competence, the need for autonomy, and the need for relatedness [15,16,42,47]. The psychological needs have been found to be positively associated with intrinsic motivation of games and independently predict enjoyment and future game play behavior [34,45].

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. Autonomy refers to the feelings of one's behaviors as self-determined rather than controlled by others. Relatedness refers to the feelings of social connectedness with others [43,44].

In this study, we apply SDT as the fundamental theory to understand how different interaction types and feedback mechanisms in the AR game influence children's perceived competence, perceived autonomy, perceived relatedness, and enjoyment level during their learning experience.

RESEARCH QUESTIONS

In order to investigate the motivational effects of the above interaction types, we designed two different prototypes in AR, which are digital screen-touch interaction and real-world tangible interaction. Secondly, we designed two different feedback mechanisms in AR, investigating the effects of non-diegetic and diegetic feedback on children's motivation during learning. We have formed three main research questions:

- RQ1: How do the two different interaction types (screen-touch and tangible) in AR learning games influence children's motivation?
- RQ2: How do the two different feedback mechanisms (non-diegetic and diegetic) in AR learning games influence children's motivation?
- RQ3: What is the relationship between interaction types and feedback mechanisms in terms of influencing children's learning motivation?

By answering these research questions, we seek to explore the design space of serious AR games to provide motivating experiences for children.

DESIGN PROCESS

In this section, we explain the methods used in our research process and how the outcomes of previous studies affect our design decisions.

Co-design with Children

Before the development of the base-game prototype, we applied a co-design method in order to involve the target children from an early process of the game concepts. We invited two primary school children aged 7-year-old (males) to co-design with us for four different sessions. The aim was to better understand the target users, elicit design concepts, and generate design implications [27].

During the first session, we found that 7-year-old children played digital games on smartphones or tablets at home during weekdays and on weekends. In the second session, children were encouraged to draw the elements they would like to have in a digital game. One of the children drew an elephant on the paper first and then apples and water around it, expressing that he would like to feed the elephant in the game. The other child drew a small farm first and then added several tall buildings next to it, explaining that he would like to upgrade the buildings by planting vegetables and raising animals in the farm. In the third session, we collected opinions from children about the types of animals and rewards they liked. Children preferred to see a greater variety of animals in the game and food to feed the animals as a reward. In the last session, we showed the initial base-game prototype to the two children with 3D animals carrying mathematics exercises walking on the physical textbook. They expressed positive feelings about it while expecting to see the animals to do more tricks. Regarding to the mathematics exercises in the game, the two children thought that they were quite easy for them to do and it might be more effective to include different difficulty levels.

The co-design process provided us with the following insights: 1) children like the ideas of animals walking on top of the book and expect the interactions to be rich; 2) the game should include exercises with different difficulty levels to be suitable for different mathematics skills.

User Tests of the Base-game Prototype

Based on the insights collected from the co-design with children, we developed the base-game prototype [28]. In this game (see Figure 2), hidden animals can be found in a children's school textbook waiting for their help to solve some mathematics problems. Children can scan the textbook to find animals and interact with them by screen-touch input, leading to several different actions of the animals, such as moving around, lying down, jumping, or flying. They can open their bag in the game containing food to feed the animals and to build a relationship with them. Once the relationship bar is filled, children can get an exercise to do. Upon completing the exercise, children receive immediate feedback showing the right or wrong answers accompanied by either a gift as reward from the animal or an encouraging message for them to keep on playing.

Two user tests were conducted comparing this AR-based game with a traditional paper exercise, first with 20 children (10 males and 10 females) in China and subsequently with 18 children (10 males and 8 females) in the Netherlands.

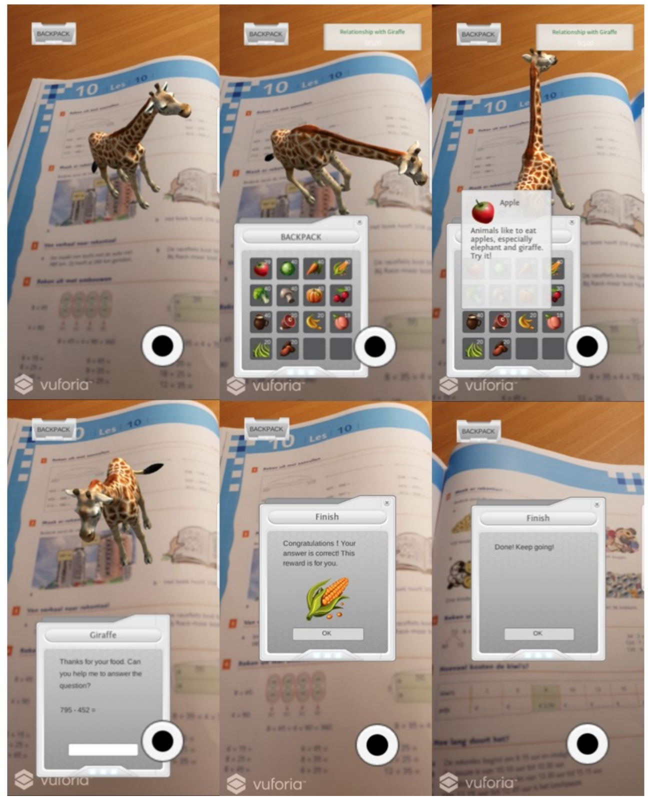

Figure 2. Base-game prototype.

From the results of the user tests, we found no significant difference between the paper or AR game on their exercise scores, showing that the AR game did not have negative influence on children's performance in doing exercises. Regarding the motivational effect, significant differences were found between children's likability of the experience, where the AR game received higher ratings in their desire to do the exercises in their free time, perceived fun of doing math, recommendation of the experience to others, and enjoyment level.

The results of the base-game prototype showed that AR game exercises were considered more fun than traditional paper exercises. Children were motivated by the game concepts of feeding and helping the AR animals while doing mathematics. However, a comparison study can suffer from novelty effects and the base-game prototype only utilizes an AR representational shell. Therefore, we decided to do a value-added study with AR specific game design principles.

Game Design

Based on the findings from the base-game prototype and the features that AR affords, namely intuitive interactions between the real objects and virtual objects and the 3D registration, we would like to explore other options in the game. We designed two different interactions and two types of feedback and developed four versions of the AR game (see Table 1).

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

Table 1. The four conditions.

Screen-touch Interaction

In the base-game prototype, children had no difficulties in interacting with the animals with the screen-touch technique. Like the base-game prototype, in this version of the game children scan the paper to find out the hidden animals and the food that carries different answers to the exercise. The goal is to guide the animal to eat the correct food by screen-touch input.

Tangible Interaction

From the user tests of the base-game prototype, we found that children expected more intuitive interactions with the 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 wanted to explore more intuitive interactions between children and the physical books with tangible interaction.

In this version, children also scan the paper to see the animals and food carrying answers. However, here we turn the paper itself into the interface with which to control the game. We calculate the change of the angles between the AR camera and the paper interface and map it onto the animals in the 3D coordinate system in real-time. Children need to turn the paper to navigate the animal and tilt the paper in order to make the animals move.

To be more specific, children can turn the physical paper from left to right or vice versa to make the animal face to the desired direction (see Figure 3 left). By tilting the paper, children can control the moving speed of the animal (see Figure 3 right). If children tilt the paper, the animal will speed up from walk to run. This interaction simulates rolling a ball on a downhill slope in the real world. Vice versa, if children tilt the paper in the opposite direction, its movement speed will slow down until the animal stops. 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 classroom setting, 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 math textbook.

Progress Bar

In the base game, a 2D progress bar showed the relationship between the animal and the player. Children informally

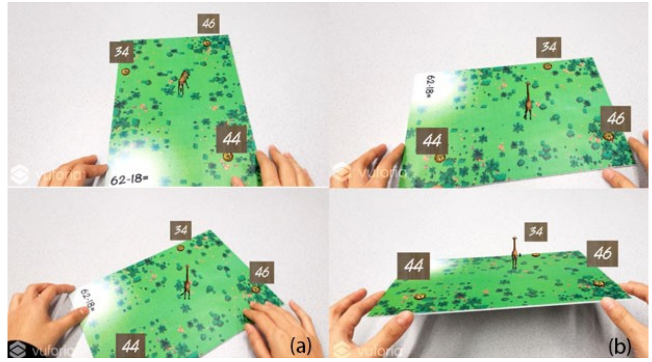

Figure 3. Tangible interaction: (left) turning; (right) tilting.

reported to have a clear understanding of the meaning of the progress bar. In the new version of the game, we applied the progress bar to provide performance feedback in an explicit way. After the animal eats the selected-food, children will see their performance immediately on the progress bar on the screen. If the answer is correct, a golden circle will appear, while the wrong answer will lead to a red circle. At the end of the game, children will see 10 golden circles if they find all correct answers (see Figure 4 left).

Progress Map

We found that children were excited about the rewards 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 AR affordances of creating a mixed reality game world. Children also expressed that they didn't want the animals to disappear after finishing the exercises. Therefore, in this new version, we introduce an interactive progress map. After the animal eats the correct answer, children can collect the animal on the map. If the answer is wrong, children can't find the animal anywhere. Children can check the map anytime they want during the game. At the end of the game, children can see 10 animated animals if the they answer all the exercises correctly (see Figure 4 right).

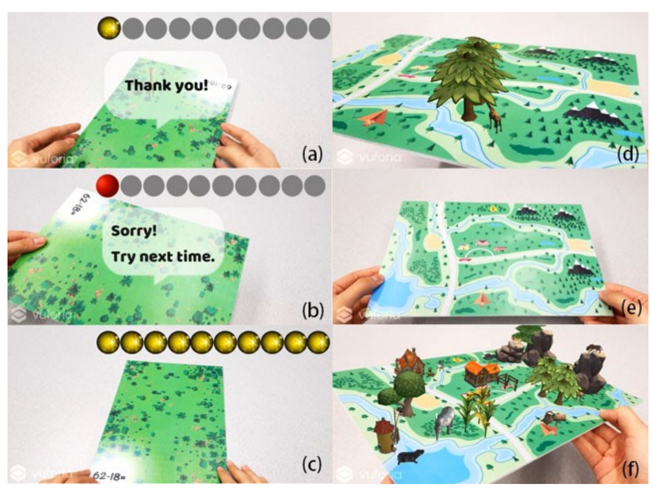

Figure 4. Different feedback mechanisms: (left) progress bar; (right) progress map.

USER STUDY

To explore the impact of the different interaction techniques and feedback mechanisms in AR game on the perceived competence, autonomy, relatedness, and the enjoyment level, we conducted an experiment with a mixed design. Different interactions were treated as a within-subject variable. This separation would help us understand what kind of interaction is more effective in motivating children to do given exercises. Different feedback mechanisms were treated as a between-subject variable since its effects might carry over to the other condition in a within-subjects test.

Participants and Procedure

A total of 32 children participated in the study (16 males, 16 females) between the ages of 7 and 8 recruited from the local city library in the Netherlands and the personal acquaintance with the researchers. All children participated in the study with both their parents' consent 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 the real-world setting. To be more specific, on the desk in the library where children can read books or on the desk at children's home. Parents were all presenting in the same room without intervening in the study procedure. The initial goal of this game was to let children practice math in after school activities, thus we chose these locations to make children feel natural and safe. We assigned children to different condition groups randomly and each child was exposed to two different interaction styles and answered the same questionnaire with randomized questions after each interaction with a counter-balanced manner. At the end of the experiment, we conducted a short interview with them.

Settings and Apparatus

The game prototypes were developed with Vuforia in Unity 3D. The experiment materials included a smartphone (Samsung Galaxy 8), a flexible phone-holder, and papers with different images and exercises (see Figure 5).

In the within-subjects study, participants finished 10 exercises with one condition and the other 10 exercises with the second condition (see Figure 6). These two sets of exercises have roughly the same difficulty level with same operators but different numbers, including 4 additions, 4 subtractions, and 2 multiplications selected from a Dutch primary math exercise book.

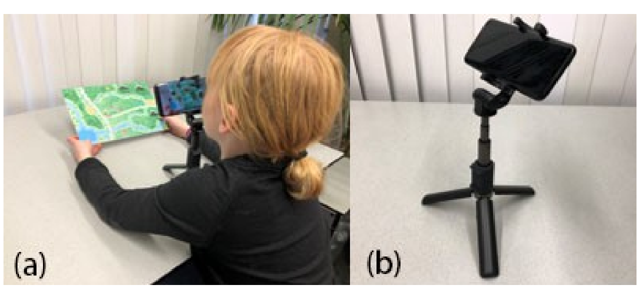

Figure 5. Settings and apparatus: (left) child playing the AR game; (right) phone and holder.

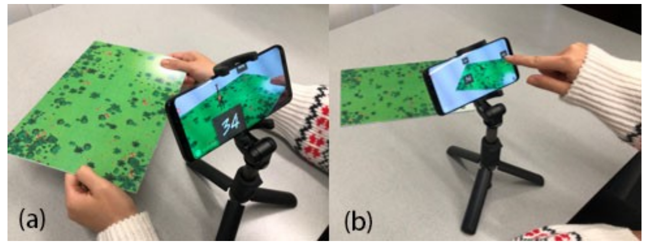

Figure 6: Experiment conditions: (left) tangible; (right) screen-touch.

Measurements

Player Experience of Need Satisfaction Questionnaire (PENS)

The PENS scale [15,43,44] was developed based on SDT for assessing the gameplay 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 the Intrinsic Motivation Inventory (IMI) [46] (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 the study of Li et.al, they 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 [28]. 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 [56]. This scale has been applied as an alternative to Likert-scale to collect reliable quantitative data from children [54]. Existing research on the Smileyometer indicates that this tool performs best for children to compare ratings between different conditions [36,39].

However, previous studies 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 [28,40,41,52,56]. Some studies suggested using a modified version of the Smileyometer to elicit more nuanced responses from children [35]. For example, to only use variations of smiling faces, or to improve the graphical aesthetic of the design by making it more colorful and visual or by using cartoon-style emoji designed for children [21]. However, the proposed alternatives have only been proved to be reliable for children aged 9-11-year-old [21]. The fun semantic differential scale developed by [56] combines photographs and semantic differential scales for young children. Conversely, this scale contains photographs for specific expressions (e.g., "happy", "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 that used the AR animated cartoon characters available from iOS. These are more colorful and visually expressive than characters used in previous research [21,56]. The facial expressions and movements were recorded by the acting of two Dutch actors. The facial expressions are 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: weak sad face and slight nodding). Figure 7 shows two examples.

The animated scales include different characters with different genders, races, and appearances since children tended to choose the character that matched their gender [54]. Children select one character and use the same character during the entire questionnaire.

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 math exercises. After each play, they answered the questionnaire using the animated scales. Children said that they could understand the meaning of the animation and rated the Minecraft higher 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.

RESULTS

Reliability of the Animated Scales

To assess the psychological needs in SDT, we applied the full scale from the original PENS questionnaire and changed the scale from a bipolar scale to a unipolar scale to improve the granularity of the responses based on the fact from previous studies that 7-8-year-old children had difficulty in understanding bipolar scales.

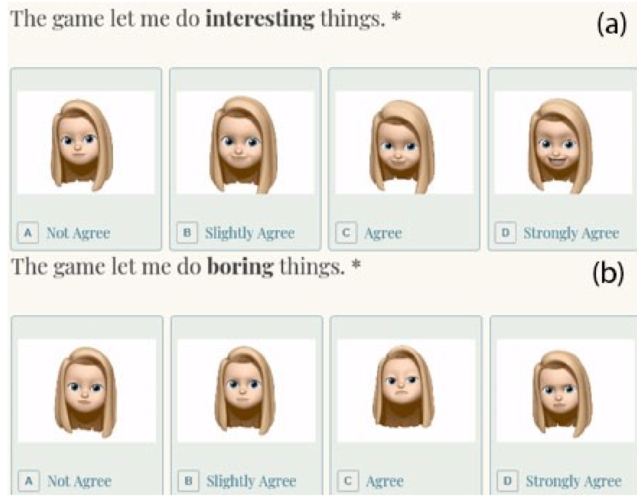

Figure 7. Examples of the animated scales: (a) Positive statement. (b) Negative statement.

Questions were modified to construct the perceived autonomy, perceived competence, and enjoyment level. Children didn't know how to answer the questions assessing their perceived relatedness and said that there was no other player. Thus, we didn't analyze the results for perceived relatedness here. The scale shows a good reliability for the perceived autonomy (Cronbach's alpha of 0.851 for the touch-screen interface and 0.77 for the tangible interface group) and enjoyment level (Cronbach's alpha of 0.650 and 0.683 respectively) constructs. However, the Cronbach's alpha for the perceived competence is poor, with 0.394 for the screen-touch group and 0.415 for the tangible group.

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 difference in the values of perceived competence, perceived autonomy, and feelings of enjoyment in relation to the two different interaction types (see Table 2).

	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)

Table 2. The average values under different interaction types.

	Competence M(SD)	Autonomy M(SD)	Enjoyment M(SD)
Non-diegetic	5.17(0.88)	4.66(1.18)	5.44(1.21)
Diegetic	5.70(0.34)	5.50(0.93)	6.23(0.80)

Table 3. The average values under different feedback mechanisms.

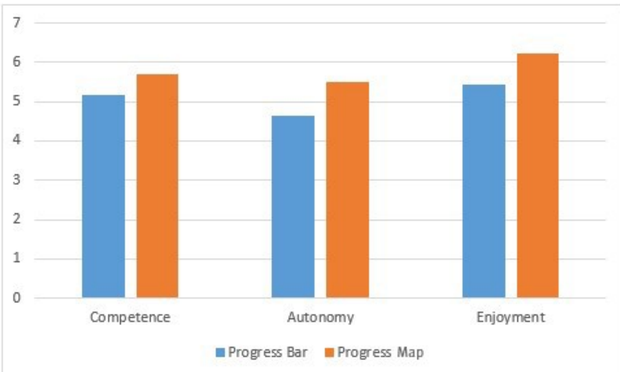

Figure 8. The comparison between different feedback groups.

Effects of Different Feedback Mechanisms

Our second research question investigates the differences between the two feedback mechanisms. To investigate this question, we performed the repeated measures ANOVA, with interaction type as the within-subject factor and feedback mechanism as a between-subject factor. Table 3 shows the average values for perceived competence, perceived autonomy, and enjoyment level in relation to different feedback mechanisms.

Figure 8 illustrates the significant effects of different feedback mechanisms on perceived competence ($F(1,30)=4.85$, $p=0.036$, $\eta p^2=0.795$), perceived autonomy ($F(1,30)=5.05$, $p=0.032$, , $\eta p^2=0.791$), and enjoyment level ($F(1,30)=4.86$, $p=0.035$, $\eta p^2 = 0.770$).

Interaction Effects

Analysis of the full models shows that feedback mechanisms yielded no significant interaction effects with interaction styles on perceived competence ($F(1,30)=0.33$, $p=0.57$), perceived autonomy ($F(1,30)=2.82$, $p=0.10$), or enjoyment level ($F(1,30)=0.58$, $p=0.45$).

Although there was no significant interaction effect, we noticed that he tangible interaction with diegetic feedback triggered the highest competence, autonomy, and enjoyment among the four conditions. While tangible interaction with non-diegetic feedback perceived the lowest competence, autonomy, and enjoyment (see Table 4). This could be caused by children feeling satisfied receiving feedback from the 2D progress bar after some interactions without spending too much time on it. While they would expect richer

	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)

Table 4. The average values under four conditions.

feedback as rewards if they put more effort into the activities, otherwise they would be unsatisfied, leading to the decreased motivation.

Interview Results

We also conducted interviews with the children at the end of the study, aiming to derive more meaningful insights from them.

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 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?

During the interview, 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"*), comparing to the tangible interaction which was more difficult and required more effort (e.g., *"it's too difficult to control"*). On the other hand, children who said that they liked the tangible interaction version more, experienced more fun during play, especially after they fully understood how the game worked (e.g., *"because it's so interesting"; "when I figured out how it really works it's really fun to play"*). Some children preferred the tangible interaction due to the screen-touch version being considered "boring" (e.g., *"the other one is boring"*).

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 is the most frequently mentioned factor (e.g., *"The animal is too small, I can't see it sometimes"*; *"You can make the paper larger, so I can make the animal walk from here to there"*). The speed of the animal moving is another factor mentioned by children (e.g., *"Animals run too slowly"; "Animals should run faster"*). 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"*).

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"*). 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"*).

DISCUSSION

Applying Tangible Interaction in AR Games

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

However, the interviews show differentiated reasons for possibly liking one over the other. Screen-touch interaction requires less effort but can make some children feel bored, while the tangible interaction has the potential to motivate children, as they found it interesting and fun even though it requires more effort. When children perceive the interaction as too difficult, their motivation could decrease. In line with Flow Theory [12], 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 [12]. 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 [36].

Moreover, the tangible interaction requires children to practice in order to grasp the precise and somewhat cumbersome controls of this interface. However, they were not de-motivated 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 [37], without demotivating them.

Therefore, we do still see potential in applying this tangible interaction implementation, when 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 [25]. The proposed tangible interaction in this paper of using the textbook to control the game can 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 and 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 generalized to different game concepts, engaging children to interact with educational textbooks more and motivating them to do their exercises.

When designing successful digital games for children, it is important for the game to be easy to learn but hard to master [6]. Designers should provide the right degree of difficulty in the AR interactions to keep children remain motivated [36]. Hence, more considerations should be taken on how to design the tangible interaction effectively. For examples, 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 but also provide children enough spaces to explore in the game?

Leveraging Diegetic Feedback of AR to Increase Learners' Motivation

Overall, our data indicate that the diegetic feedback (progress map) was significantly preferable over the non-diegetic feedback (progress bar). When receiving feedback through 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, in that intrinsic motivation does not increase solely due to higher feelings of competence unless it is also accompanied by an increased feeling of autonomy [43,44]. Even positive feedback may impede people's inherent need for autonomy and thus decrease their intrinsic motivation [14].

Moreover, when designing for motivating and immersive experience for children, we suggest designers utilize the special affordances 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 classroom.

Limitations and Future Work

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 shows 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 didn't 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. In the future, we will address and test how our iterated AR game influences children's learning outcomes. Besides, we didn't collect additional information from the participants, such as their current math ability and attitudes towards it. Differences might exist among the participants especially because they came from different schools in the Netherlands, which may influence the motivational effect as well.

In the discussion we hypothesized that the two interaction types may 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.

The learning content and the game mechanisms are decoupled in the current AR game. The goal was to explore design guidelines to create motivating AR learning games for children. How to integrate learning content more authentically and effectively in our approach is something we are still scrutinizing.

In the future, the current prototype will be iterated upon, integrating other game design paradigms such as social connectedness. By doing so, we seek to build a systematic understanding of the design space of serious AR games and the ways in which it can improve motivation for learning in children.

CONCLUSION

In this study we investigated how children 7-8 years old react to two different interactions styles (screen-touch versus tangible interaction) as well as two different feedback mechanisms (a non-diegetic progress bar versus a diegetic progress map) when performing math exercises in an AR game. There was a significant effect of feedback mechanisms 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 feedback and interaction type. 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. Possible limitations in our work include the modified scales and the lack of focus on the learning outcome. We are aware of these concerns and will address them in the future.

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