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Researching Adaptivity for Individual Differences in Numeracy Games

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Abstract

There is increasing evidence that mathematics video games can play a large role in mathematics education, in support of children's learning. However, despite the interdisciplinary nature of the subject, research in this area has traditionally been fragmented between disciplines. The RAIDING project was conceived to bring together researchers in neuroscience, maths cognition, and game-based learning to develop a maths game that can act as a research platform for furthering knowledge in this field. The game will employ free-to-play design elements, alongside an adaptive learner model to investigate how children learn maths, through a range of empirical studies.

Author Keywords

Game Based Learning; Mathematics Cognition; Free-to-Play; Analytics; Adaptivity

ACM Classification Keywords

K.3.1 [Computers and Education]: Computer Uses in Education; K.8.0 [Personal Computing]: Games

Introduction

There is a growing body of evidence that suggests that videogames can play a large role in mathematics education, in a number of related ways. Games can be used to support children's learning, as well as being used as a means of assessment and also as a tool to research how children develop their mathematics cognition. However, the current research is fragmented [17][21][10], and the vast majority of reports in this area are simply evaluations of individual games, with small sample sizes. Furthermore, research in this area has traditionally been fragmented between disciplines. The RAIDING project aims to explore the links between the various disciplines, and to combine techniques from across the varied research to produce a viable maths education game as a research platform for empirical work.

Emerging neuroscience research is providing an improved, more recent understanding of motivation and reward, and its effects on cognitive training environments. The project will be applying this new research directly into the relevant aspects of primary mathematics teaching and learning. To aid in data collection post-studies, the project will be using the mobile app stores (both Android and iOS), as well as analytic systems to expand our evaluation beyond the traditional classroom and laboratory environments.

Research involving videogames and mathematics rarely involves researchers from other disciplines such as psychology, mathematics education, neuroscience, and computer science, whereas this project will utilise a varied range of research from across these fields.

Background

The project has a background in three major areas: mathematics learning; psychology and neuroscience of games for learning; and game design and analytics.

Mathematics Learning

The project is focussing upon a fundamental aspect of maths learning - the development of symbolic number sense. This occurs in the first two to three years of primary education, and is essential for later mathematical learning.

A fluid number sense allows for the rapid (if not automatic) retrieval and manipulation of stored information, relating to number. Many of these processes are unconscious, but are important components of children's learning of mathematics. [15] Furthermore, fluency of number sense means that children can solve problems by using their knowledge of relationships between numbers. This is also beneficial to the development of other aspects of mathematical thinking and problem solving. This project aims to explore how the rates and means of acquisition of these skills differ on an individual level, as well as the effect that these skills has on other aspects of mathematical activity.

Contemporary video game platforms offer significant promise as a tool for researching how children develop these skills, due to their ability to capture large amounts of data relating to children's individual learning trajectories. Furthermore, they offer a good environment for the development of number sense, due to the quantity of problems that a video game can generate, compared to more conventional methods. They can also be adaptive in their delivery of content to keep pace with a child's own individual learning trajectory. Nonetheless, many of the existing maths learning tools are not founded on theoretically sound principles, and do not integrate the mathematics directly into the gameplay.[17][13]

Psychology and Neuroscience of Games for Learning
Insights from neuroscience are revealing the processes in how games can effective in engaging the brain's reward system, and that provides some insight into how games can accelerate the rate of learning [10]. There is a long history of motivational theories of game design for learning [19], but only recently have neuroscience techniques been able to demonstrate their learning benefits; for example:

1. Uncertain Reward [14]
2. Cue/goal-directed action [12]
3. Cooperation and/or competition [9]
4. Adaptivity [8][1]

Other aspects of game design that are likely to affect learning and motivation can be inferred from the maths education literature, but have not been tested yet in a game environment, such as timed tests, and the individual responses to such tests. There is evidence that timed tests are a significant cause of mathematics anxiety amongst primary school children [11].

These game attributes have sometimes been investigated individually, but rarely in combination, and never in interaction. The project aims to explore how the results of separate and combined testing of these aspects effects on learning.

Analytics
Current research is showing how analytical process data can be used to investigate how game design effects motivation, engagement and learning. [4][22]Large data sets created from game analytics can be used to more fully explore the mechanisms of effective learning with games, rather than just the outcomes. This project aims to explore the potential to use formal concept analysis [2] to reveal meaningful relationships between game features and individual player characteristics, as well as providing conceptual models as a basis for adaptive content.

Game Design
Connolly et al. [10], in their review of serious games, have found that there is a lack of high quality evidence regarding the impact of games, and the outcomes for learners. There is a distinct lack of research on what makes a game a good platform for learning. Research often focuses on individual games and the studies rarely make comparisons of key design variables. Furthermore, the studies are from a wide range of fields, but rarely align with each other and few links are made with psychology, neuroscience and education.

While exemplar's do exist [6], many commercial examples still treat their mathematical content as a separate task, a roadblock in the game to be overcome with reticence and reluctance, rather than as part of the core gameplay. This 'chocolate-covered broccoli' approach [7] is employed in contemporary examples such as Star Dash Studios [20] and the Times Table Adventure [23]. In these games, the mathematics is confined to specific points in the game, representing a fraction of the total experience and having little connection with the core gameplay and strategy. The games could have been made without any of the mathematics challenges and provided an almost identical gameplay experience.

Figure 1: Flying around space.

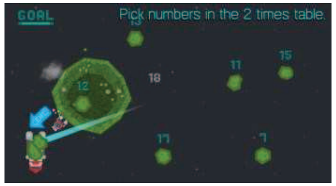

Figure 2: A times table mini-game.

Figure 3: Conversion of credits and gaining seeds.

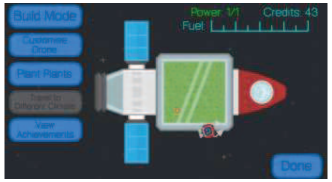

Figure 4: View of the base.

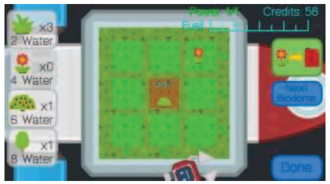

Figure 5: Planting in progress.

Gameplay Overview

The game is designed around touch-screen controls on tablet devices. The player controls a small robot, which explores an area of space around its mother ship in search of asteroids to "mine" Each time an asteroid is found, the player begins one of the maths based mini-games which make up the core of the gameplay experience. This arcade-like gameplay allows the player to earn game currency for completing mathematical tasks as they mine the asteroids. The mining products return to the mother ship in slow moving "carts", and are exchanged for "credits" when they get there. The player also has a random chance of finding seeds within asteroids which can be planted back at the mother ship. The difficulty level of the mathematics is determined by a dynamic learner model maintained by the game.

The player then can return to the base to plant their seeds, or upgrade the base using the credits that have collected. Seeds take time to grow into plants which provide a habitat for alien life or can be converted into fuel so that the mother ship can travel to other regions of space with contrasting flora and fauna. The player then returns to mining more asteroids. This overall loop continues across gameplay sessions and the goal is to build bigger mother ships and attract the widest range of alien life to live within its biodomes.

Game Design and Adaptivity

The central goal of the game design was to ensure that the mathematics was intrinsically part of the core gameplay, instead of being superficially "bolted on". The mathematics is the main repeatable gameplay activity of the core loop and occupies the majority of the player's time spent playing the game. The credits and seeds obtained from the maths based mini-games are required to do any other action in the game.

There is also a waiting component of the core game loop as the "carts" return to the mother ship. As these carts are a limited commodity, this creates a "sessioning" mechanic for the game. Sessioning is simply "showing the player an exit for the play session" [18]. Sessioning often "works by limiting the number of core loops that can be played by introducing a limited resource." [18] In our game, this concept is represented both by the carts that are limited in number, but also the seeds that are granted as a reward. The limited number of carts restricts the amount of mining a player can do, and this aids in the retention of players, as it stops the player from overplaying the game. Players will eventually tire of any gameplay, but they are much more likely to return if they leave before they reach this stage [18]. This approach supports the educational concept of spaced learning, with research by Kelley suggesting that learning is best done in 20-25 minute blocks, with gaps that are at least 10 minutes in between each session [16]. Ideally, for this game, the gaps between each session would be somewhat longer, in the order of 1-2 sessions each day.

Another key component of retention is the concept of "return triggers". A return trigger is simply something that makes the player want to return the game. There are multiple types of return trigger, such as the appointment trigger (return at a set time for a reward), competitive trigger (such as leader boards, player vs player content, etc.), and social commitment trigger (when a player's response is needed for another player to continue) [18]. In this project we use appointment

Learner Model Internals

The learner model that has been developed for the game determines a child's level of mathematical skill, based upon research done by Ashcraft on chronometric approaches [3]. For each times table and set of number bonds, it stores the confidence for each number in that times table and number bond set.

This is calculated by taking a rolling average of a player's accuracy and how long it takes them to select a correct answer, and converting this into a zero to one range of confidence.

This value is then used by the learner model to return a set of probability values for the random number generators in the game. These determine what times table/number bond set the player will get next, as well as the frequency of values within that set, so more are generated where learning reinforcement is required.

triggers, in the form of the carts returning to the base full of credits, and seeds growing into plants. Both grant the player a reward and allow the player to take part in additional metagame gameplay

The metagame is a major part of the game design, in which the player can upgrade and customise their mother ship. In particular, additional biodomes can be purchased to house additional plant and animal life. Biodomes provide a grid-like structure for growing plants (figure 5), but planting is not just about creating aesthetically pleasing arrangements, as their placement is constrained by their water supply. Each plant uses a certain amount of water, and there is a limited supply per row and column, requiring the player to think carefully about their placement. The water system adds a small, additional amount of maths, and reinforces the maths focus of the game. The plants are also key to progression in the game, as they can be converted to biofuel which allows the mother ship explore new regions with different climates. The different climates introduce more content with different types of plants, and require additional biodomes to be added to the mother ship. All of this progression requires credits and/or seeds, and these can only be gained by playing the mathematics mini-games. This metagame fuels the economy of the core gameplay loop, requiring the player to play maths games to earn even more credits, as they spend credits on additional content.

Adaptivity

One other key part of the game design is the adaptivity provided by the *learner model*. Critically this has been deliberately designed to be decoupled from the player's progression in the wider metagame. Thus the learning content of the game is always determined by the player's mathematical performance rather than their accumulation of credits or size of their mother ship. Based on the research done by Ashcroft and the chronometric model of learning [3], the learner model drives the mathematical difficulty of the game. When a new player starts the game, the learner model is empty, and is limited to only allowing certain mathematical elements to be played. As a player demonstrates mastery of these mathematical elements, the learner model unlocks additional maths challenges, and reduces the frequency of the older maths challenges (while not removing them altogether). Mastery is determined by first demonstrating a high level of accuracy, then a fast response time (roughly 2 seconds). This also ties into our analytic solution, which is discussed above. The learner model uses the analytic data to determine whether a player has gained the required level of accuracy and response time at the end of each mini-game session, and then updates the stored learner model with the new data. This is key to the mathematical skills development, as it means that a player cannot be "left behind", as the learning content will move at the pace determined by the players mathematical performance, and increase the challenge based on the analytics gathered.

Iterative Development

Iterative development and testing have been at the core of our agile software methodology. Weekly meetings allow all aspects of design and development to be discussed alongside progress reports and play testing. While some key elements of the design (such as sessioning and return triggers), were in place from the beginning, the maths mini-games have evolved iteratively in response to regular testing and feedback.

So far, the game has had undergone 3 main testing stages with children to inform the iterative development. The first were performed with a small group of children using a pre-alpha version of the game. At this point, barely any of the major systems were implemented, and the testing was mainly used to generate suggestions from the children, determine if it was enjoyable and find issues with the game. Once the main mini-game and analytics systems were in place, a larger testing session was undertaken involving 50 children visiting the university. This was used to both test the analytics as well as gather more suggestions and comments from the children. The third test was performed at a local primary school, and was used to ensure that the learner model was working and producing valid results, in addition to gathering comments and suggestions. At each stage the children's feedback and testing has usefully informed the direction of the game design in ways that would not have been possible without the insight of target users.

To aid in iterative development, source control techniques such as branching have been used to great effect, allowing new features and alterations to be prototyped rapidly without affecting the core game as well as allowing for simple integration of new features.

Future Plans

The next step for the project is going take is to perform a full randomised control trial of the game to investigate which, if any, of the features have an effect on the children's learning, and how much of an effect if it has. This will include pre and post testing, as well as thorough analysis of the data that the analytics captures to inform the ongoing design of the game. The experimental trial will have 8 variants of the game produced for it, one control with none of the features enabled, one version with every feature enabled, and then 2 versions with a different feature enabled/disabled. The 3 variables that will be altered in the versions are whether or not moving objects affects learning, whether or not an uncertain reward will affect learning, or whether having a visible time pressure will affect learning. These variants will be given to different classes for two weeks, and at the end of the two week period, we will analyse the data recorded using the analytics to determine any effects, and the level of such effects, if it exists.

In the longer term, the aim is to launch the application as free app on the Apple and Google Play stores, in order to recruit a larger playing audience from which larger amounts of data can be gathered.

Summary

We feel that the game we have produced has a great deal of potential and the overwhelming majority of feedback received has been positive. With further testing, balancing and polishing, we believe the game can become a successful educational app which takes a clear step away from the 'chocolate-covered broccoli' approach so typical of educational computer games. More importantly though, it will provide a platform for exploring a range of research questions pertinent to learning in mathematical games and help to inform our understanding of what makes an educationally effective mathematics game.

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