Visual Spatial Math Training Tool: An iPad Application for Training Visual Spatial Abilities in Preschoolers

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Abstract: In this paper, we present a full-fledged educational iOS application called *Visual-Spatial Math Training* (VSMT), which has been developed to improve cognitive abilities in preschoolers. VSMT is a tablet-based application that has been designed for the iPad and implemented in the Swift programming language, using the native SpriteKit framework. VSMT provides the means for working with a wide range of geometry puzzles (games) in addition to offering a solution verification engine that can verify user solutions. The main purpose of this application is to strengthen the visual-spatial abilities in young children in order to provide them and their instructors with a better foundation for understanding and teaching mathematics, respectively. Finally, we describe a series of experiments carried out using the VSMT application during special training and assessment sessions in several kindergartens in Luxembourg with over 60 pupils.

1. Introduction

In recent years, the use of modern media and tools such as hand-held and mobile devices has received more and more attention from the pedagogical community (Druin & Fast 2002; Plowman & Stephen 2003). This includes either using existing tools and applications provided on mobile platforms, or designing entirely new applications for specific purposes. Among the wide range of existing use cases, an important area of research is the design and development of interactive visual environments for manipulating objects/shapes geared towards educational ends.

In this work, we first present a framework and architecture that we have developed for processing geometry puzzles. Next, we present an iOS application, mainly designed for the iPad, that we have designed and developed using our framework. Our application has been used in 5 Luxembourgish kindergarten classrooms as a training and evaluation tool for visual-spatial abilities of around 70 children over a 10 week period of training sessions (Cornu, Pazouki & Martin 2015). The presented work describes a complete and fully developed theoretical framework and iOS application that has been tested in Luxembourgish kindergartens.

1.1. Research Context

The goal of this application is to train and evaluate the visual-spatial abilities in young children in order to provide them and their instructors with a better foundation for understanding and teaching mathematics, respectively (Cheng & Mix 2014). Students with language deficits are a vulnerable group for low mathematics performance, resulting in lower academic achievement throughout schooling. This is of special interest for the Luxembourgish school environment, due to its high number of pupils with migratory background.

The inherent difficulties of such approaches were discussed in (Alt, Arizmendi & Beal 2014; Beal, Adams & Cohen 2010). Due to the requirements of our research, the targeted users are mostly between the age of 4 and 7 and cannot read. For this reason, the application is designed in such a way that it does not depend on language skills at all and is free of any text or speech. In our approach, we first train pupils using a predefined set of exercises and then evaluate their improvements in subsequent similar exercises.

1.2 Related work

Although there are a few applications that only allow the user to draw primitive objects on a grid, as far as we know, there are no academically motivated projects offering similar capabilities for a language free tool designed for training visual-spatial abilities in preschoolers on tablet devices. More specifically, our system not only provides support for processing a wide array of puzzles, but also, more importantly, it has native and built-in support for verifying user solutions using a dynamic solution verification engine.

(Zaranis, Kalogiannakis & Papadakis 2013) propose the integration of mobile devices with custom applications in kindergarten classrooms for teaching mathematics. (Couse & Chen 2010) had children draw on the tablet devices but they did not include specifically designed tasks tailored to their study.

Regarding projects that target learning in preschoolers by using tablet-based approaches for enhancing user performance in different subjects, most existing systems are in the form of simple games that offer limited and a predefined set of operations (Kiili, Ketamo & Koivisto 2014).

1.3 Contributions

Our work has two main contributions. First we present an extensible and dynamic architecture specifically designed for handling geometry puzzles and for an automatic verification of user solutions. We have used our architecture to develop a generic framework for representing interactive visual-spatial puzzles that allows users to manipulate shapes using a wide range of techniques. Our solution has been adapted to hand-held devices, which have limited processing power and battery. Another advantage of our framework is that it includes an independent module for verifying solutions provided by the user for a well-defined group of different puzzles. Since the solution verification element is completely detached from the rest of the framework, it is quite easy to design and add new puzzles to the system.

The second contribution is an iPad application, developed using our theoretical framework, which is capable of processing an interactive environment for manipulating geometric shapes in order to solve a wide range of different puzzles. The application includes a generic solution verification engine for geometry-based puzzles. Our modular and component-based design simplifies the addition of new types of puzzles and their verifiers. Finally, our application includes a built-in activity monitoring module, which constantly monitors and records both user and system activity events and generates detailed logs for future studies. The current version of the application supports more than 15 different puzzle categories focusing on different aspects of visual-spatial abilities, which amount to an overall number of 2000 puzzle instances.

1.4 Structure

The paper is structured as follows. In Section 2, we describe our framework and explain the architectural design decisions for its extensibility. We then describe the iOS application that we have built using our framework in Section 3. Section 4 is dedicated to describing the built-in activity monitoring and in Section 5, we briefly report on experiments carried out in Luxembourg using our application.

2. A Generic and extensible framework

We briefly describe the main ideas behind our extensible design, puzzle creation process and the verification of user solutions.

2.1 Extensible design

Our design relies heavily on polymorphism and incorporates essential concepts from object-oriented programming such as encapsulation (Weisfeld 2008; Coad & Yourdon 1991; Vlissides, Helm, Johnson & Gamma 1995), which as a result, fosters reusability and extensibility.

At a very high level, as shown in (Fig. 1), the system transitions between the two states of control center (CC) and puzzle screen (PS) via a middle layer, referred to as the transition management module (TMM), which manages these transitions. TMM has access to a component called the "Task Launcher", which retrieves the next task instance depending on parameters such as the current level and selected puzzle type. The tasks or puzzle instances returned by the task launcher all implement the same interface, meaning that the puzzle screen does not need to know how the selected task works as long as the task can reply to its queries. When a puzzle is selected and running, the system loops in the puzzle screen state and receives input from the user and forwards them down to the corresponding event managers.

The Grid, which is the central functional element of the system brings all these elements together and also acts as a hub and interface to other modules. For example, each task category only has access to the API of the Grid and to access any information about the grid's state and all the shapes inside it by simply calling the appropriate grid interface functions.

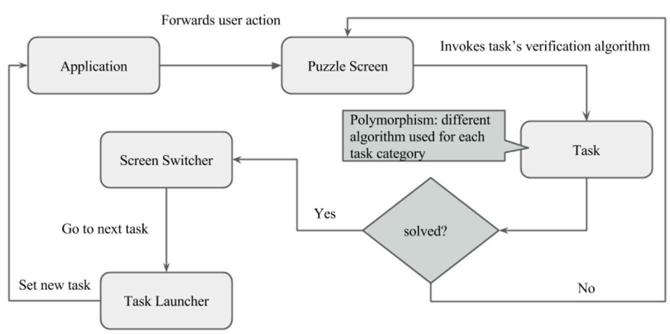

Figure 1 A simplified diagram of the logical flow of VSMT

2.2 Creation of New Puzzles

Puzzles are represented on a grid made of a set of nodes and edges. Puzzles are thus described as a collection shapes described by graphs. An important example of our solution verification oriented design is the following: For many puzzle types, we create two sets of edges, one for edges that should initially appear on the grid and another defining the edges that are expected to be drawn by the user to complete the puzzle. Using this simple method, many different kinds of puzzles can use the same verification algorithms.

2.3 Solution Verification Engine

The solution verification engine is designed in such a way that it is completely isolated from the rest of the system and therefore, it acts as an independent component. This design decision, in addition to the properties of the framework as a whole, makes it possible to verify a wide range of geometry puzzles by re-using and combining a series of more primitive solvers.

The verification module interacts with the rest of the system via a simple mechanism that simply replies "correct" or "incorrect" to requests from the application, which can be generated at various times depending on the puzzle type and the current task. When the verification module receives a request, since it has access to the entire grid and everything contained in it, it runs its verification algorithm and replies with a "correct" or "incorrect" message.

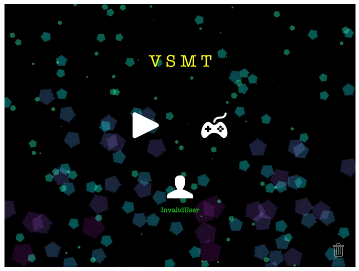

Figure 2 Main screen of the application

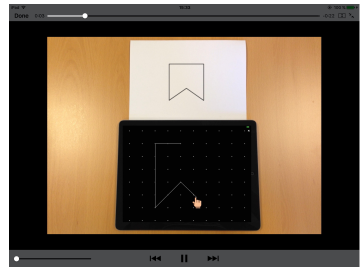

Figure 3 Tutorial video screen

Any new verification system needed for new puzzle types can be added to the system without having to know how the rest of the system works. As long as the new verifier replies with a simple "yes/no" answer, new verifiers and puzzles can be added to the system in a seamless manner. A set of simple rules can be then defined for the verification of user solutions such that the system can automatically verify user solutions without further intervention by the designers of the puzzles.

3. iPad application

Here we present the iOS application that we have developed based on our framework. The application supports four different groups of users. The first and most important group corresponds to the actual trainees who use the application for solving puzzles. Second, the designers of new puzzles, who can be researchers or teachers working in kindergarten or elementary schools. Third, developers who would like to extend the system to support new types of puzzles and solution verifiers and additional functionalities. Finally, researchers who are interested in evaluating user behavior in different tasks by monitoring their activity and progress through the built-in monitoring mechanism.

3.1 Brief overview of technicalities

The application has been implemented entirely in the Swift programming language and uses the native SpriteKit framework and no third-party components. The implementation follows the object-oriented paradigm and the software engineering has been done with great emphasis on reusability and extensibility. In short, we have applied well-known techniques from software engineering such as design patterns in order to have a robust and flexible design.

3.1 How the application works

Here we will explain a complete cycle of the application using screenshots. (Fig. 2) shows the main screen of the application, which is the launching screen allowing the users to log in by clicking on the avatar and scanning their ID card. When users are logged in, they are able to start a puzzle by clicking on the play button on the screen and then scanning the QR code of the chosen puzzle as depicted in the booklet. The screen transitions to playing the tutorial video screen (Fig. 3) of the selected puzzle type. The booklet is a supplementary physical book containing the puzzles with their corresponding QR code.

QR codes are used in the booklet to run the tasks as a means of controlling the school settings and to give the teacher the possibility to decide, which task pupils should work on. When a specific puzzle P is to be played, the teacher distributes the booklet for P to the pupils, which they then use for launching their puzzles. Before a puzzle starts, a tutorial video is played to explain the objective of the selected puzzle.

For example, for the task shown in (Fig. 6), the user is supposed to draw the symmetric form of the shape. It is possible for the user to play the tutorial video again by clicking on the "play" button or to restart the task by clicking on the "refresh" button. They can also go back to the home screen by clicking on the "back" button.

The user can draw lines by connecting the grid nodes and remove them drawing the same line again. As soon as the user draws all the expected edges the task will finish and the user will get a notification using a smiley face on the screen and then the next level will load on the screen. More samples of the puzzle screen regarding different types of puzzles are shown in (Fig. 4, 5, 6, 7, 8, 9).

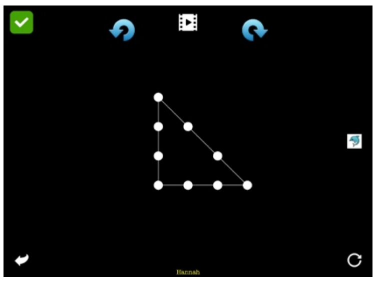
Figure 4 Rotation puzzle

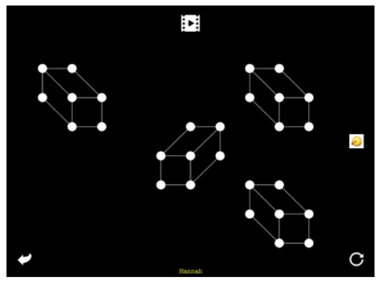
Figure 5 Select the odd one out

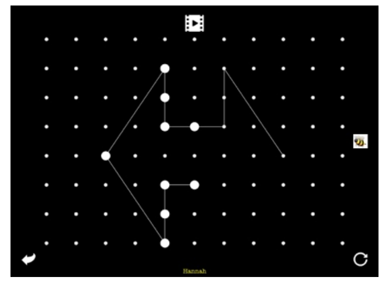
Figure 6 Symmetry

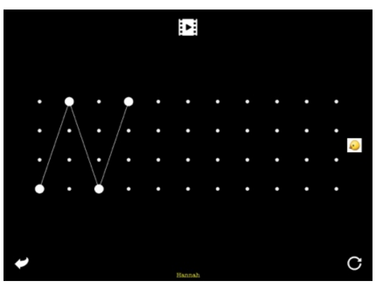
Figure 7 Pattern completion

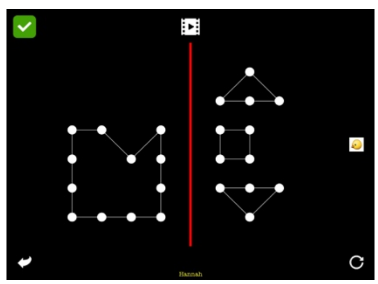
Figure 8 Jigsaw

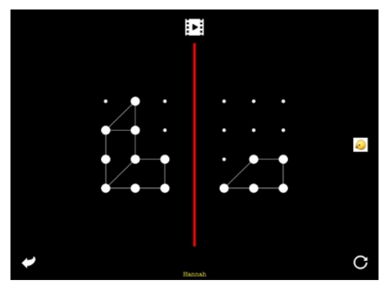
Figure 9 Copying

3.2 Built-in Puzzle Types and Supported User Actions

Here we give a summary of a subset of the built-in puzzle types. For puzzles of type drawing, the user should draw a set of lines on the grid in order to create certain shapes or to complete a pattern. For selection-based puzzles, a set of shapes appears on the screen and the user should select one or several predefined shape(s) from the other shapes. In the rotation category, a shape will appear on the grid and the user should rotate the shape on the grid (by clicking on the rotation buttons on the screen) in order to put it in the same orientation that is depicted in the booklet. In the coloring category, users must color an appropriate shape on the screen based on the depicted shape in the booklet and finally, in movement based puzzles, a set of shapes is shown on the screen, and the user must move (by using drag and drop) them and place them next to each other according to a certain arrangement that is shown on the booklet in order to complete the puzzle.

A large number of different tasks targeting different aspects of visual-spatial abilities were developed and implemented using the VSMT application. A small subset of the tasks with short descriptions is provided in (Tab. 1).

Table 1 A short subset of tasks with their short description

Task	Description	Booklet	Type
Tangram	Rearrange shapes to match the configuration presented in the booklet	Yes	Move
Completion	Complete a figure based on the provided correct form	Yes	Draw
Find the pair	Finding two shapes that are the same amongst distractor shapes.	No	Select
Bisection	Mark midpoint of a line.	No	Select
Coloring	Color the shape, depicted in the booklet.	Yes	Color
Rotation	Rotate the shape according to the orientation depicted in the booklet	Yes	Rotate
Free Play	User can draw and delete freely, no QR code required.	No	Draw

3.3 Free Play

The application also provides a free play mode, which does not require a booklet or QR code to run. The free play mode provides the user with an empty grid on which they can draw and delete shapes with no limitations. This allows the children to explore the basics of the application by freely drawing and deleting lines. The free play mode was initially the starting point and one of the main use cases of project as it can be used for studying how pupils learn to manipulate the system, but also to study their visual-spatial skills.

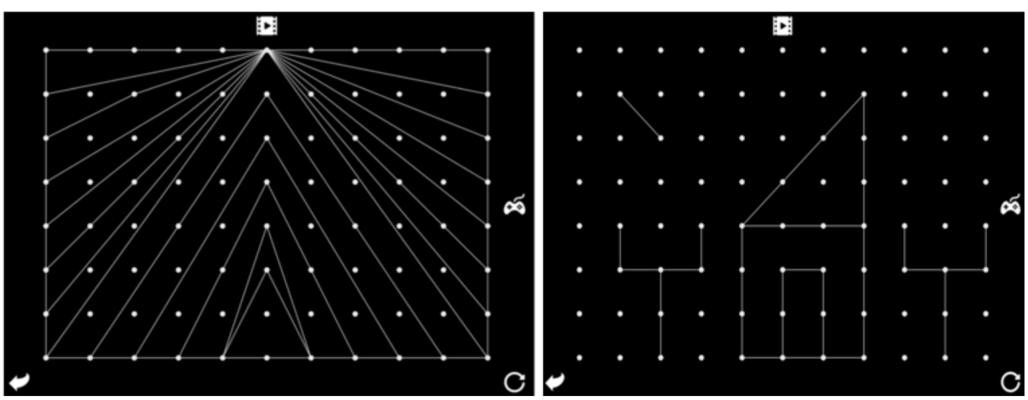

Figure 10 Screenshots of a user's drawings done in the free play mode

Since all events are logged, free play sessions can also be used for studying user behavior. The application also takes a screenshot of their drawing as shown in (Fig. 10) for future reference, for both teachers and students.

3.4 Language Free

The fully visual design of the application is independent of any language requirements such as text or voice-overs. As users are mostly young children between the age of 4 and 7 and cannot read, the application is free of any text or speech. This means that no matter what language the user speaks, the application can still be usable. This language free version makes it possible to use the tool in multilingual settings such as the Luxembourgish school environment, due to its high number of pupils with migratory background.

3.5 User Management with QR Code

For user management and user identification, we use a QR code scanning mechanism so that users do not have to type in any user IDs or passwords. Therefore, users require an ID card containing a QR code. Upon scanning a valid QR code, the system will log in to their account and after that they can start using the application. The system also stores user progress so that pupils can resume their tasks at a later time.

4. Built-in monitoring and logging

The system records all system and user actions into log files. Our logging follows an event-based approach, i.e. recording all the events issued by the system and the user, while the user is working with the application. This mechanism can be helpful for researchers who seek to evaluate the performance of pupils in different tasks or to find patterns in their behavior or approaches in solving the puzzles. Logs are designed in such a way that they simplify post-processing and analysis of the recorded data.

5. VSMT used in Luxembourgish schools

Our system was used in the spring of 2015 (from March to June 2015) in 5 Luxembourgish kindergarten classrooms as a training and evaluation tool for visual-spatial abilities. In total, 68 children participated in the training sessions. The training took place over a ten week period with two sessions of twenty minutes per week. The project was carried out in the context of a PhD project at the University of Luxembourg focusing on the effects of visual-spatial training on children's visual-spatial abilities and early math abilities prior to formal schooling.

Moreover, the VSMT application is currently being used in sixteen schools across Luxembourg in the context of small-group interventions with 93 language minority children to assess the effects of a primarily non-verbal visuo-spatial intervention in a multilingual school context. In a second phase, the intervention will be extended and it will include early numerical tasks targeting children's basic math competencies (Cornu, Schiltz, Pazouki & Martin 2016). We would like to mention that although the application and the framework presented here are complete, it will be continuously extended with new puzzles for future experiments.

6. Future Work

In addition to a series of future developments ranging from adding support for new reusable puzzle types, concrete puzzle instances and generic verifiers for various categories, we intend to pursue two specific projects.

In a first step, we intend to develop an entirely new component that would equip the existing application with a highly customizable editor. This editor would be enhanced and further developed into an authoring tool, which would then be used alongside the main application. Such an authoring tool would allow non-technical users such as researchers with no background in programming who are specialized in human and social sciences to develop entirely new sets of puzzles and their corresponding solution verifiers. This requires a common set of verification rules and puzzle construction primitives that are highly reusable and that compose with each other in order to create more complex puzzles.

The second plan for future work involves the integration of a data analysis tool into the VSMT application. For the moment, we have developed post-processing tools for performing data analysis on the log files generated by VSMT. However, an integrated data analysis module would instead perform its operations in real-time and provide summarized result sets in the form of tables and graphs at various stages.

Finally, in the upcoming sets of puzzles that we intend to implement, we will focus on puzzles dealing with numerical development as opposed to the visual-spatial puzzles that are currently implemented. Moreover, an assessment mode will be added, which would silence the notifications issued by the solution verifier so that we only display a final mark once all the puzzles instances are solved, but not after each verification.

7. Conclusion

We have presented a generic and extensible framework for building interactive visual environments for manipulating and solving geometry puzzles on hand-held touch-based devices. We have also presented an iOS application, called VSMT, mainly designed for the iPad, that has been built using our framework. VSMT is a dynamic and easily extensible system for visual representation of geometry puzzles with a built-in set of solution verifiers for a wide range of puzzle types.

We also presented a solution verification engine that is independent of the other modules in the application. This verifier is capable of handling a series of puzzle types, with the added benefit of providing support for generic puzzle primitives that can be reused for the verification of similar puzzles. We described its decoupled design, which allows the addition of new solvers without them having knowledge of how the rest of the system works.

Furthermore, we described how our system provides native support for constant monitoring of system and user activity using a detailed event-based logging mechanism that records every important event caused by the system and the user.

Finally, we reported on a series of experiments carried out in various kindergartens in Luxembourg in order to train and assess the visual-spatial abilities and math abilities of preschoolers.

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