Cognitive Predispositions of Students for STEM Success and Differences in Solving Problems in the Computer Game for Learning Mathematics

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Abstract—STEM education forms a basis for an innovation-based society. Mathematics is, besides being an integral part of STEM, also a prerequisite for success in mastering remaining STEM constituents. With the aim of early detection of gifted students, i.e. students who would be able to follow advanced forms of teaching and be successful in STEM, this paper analyses cognitive predispositions of students gifted in Mathematics and the differences in their ways of solving problem tasks in the computer game for learning primary school Mathematics. Additionally, the paper analyses success related to finishing different levels of the game.

Keywords—M-learning, e-learning, game-based learning, STEM, gifted students

1 Introduction

Historically speaking, the industrial revolution marked the beginning of STEM (Science, Technology, Engineering, Mathematics) education importance [1]. STEM area is nowadays used as a basis for transformations in the development of modern society.

STEM approach gives an interdisciplinary view with a positive contribution to creativity, critical thinking, problem solving, and higher levels of skills acquisition [2]. Successful implementation of high-quality STEM educational programs and curricula implies, among other things, the use of suitable technology, such as modelling, simulations, and distance learning for enhancing experience related to learning and research. In order to facilitate innovativeness, the strategies of teaching should include problem learning, project learning, and collaborative learning [3].

Forms of teaching and e-learning suitable for teaching STEM-related content as early as in primary schools need to be carefully examined, in order to make them interesting to new generations of students who grow up in the digital age, and with the goal to later engage as many of those students in STEM professions. The implementation of e-learning in primary schools is additionally burdened by problems such as availability of the system, student motivation to use the system, as well as collaboration in problem solving.

Since Mathematics is an integral part of STEM and since it is considered a prerequisite and the basis for mastering the remaining STEM constituents, this paper examines the possibility of early detection of students gifted for Mathematics exclusively through their interaction with an educational computer game. Students gifted for Mathematics are considered to have predispositions for success in science, technology, and engineering education. The idea is to detect them already before they decide on their future career and thus guide them into STEM.

For the purpose of this research, and in agreement with the teachers of Mathematics who participated in this study, the students gifted for Mathematics are defined as those able to follow advanced forms of teaching, i.e. additional classes in Mathematics. Therefore, hypotheses explore whether there are difference between students who take classes in additional Mathematics and those who do not regarding the accuracy in solving problem and regarding the way they finish levels where multiple solutions are possible. The related work is presented in the following section. Section three sets out the context of the research and gives precise formulations of the hypotheses. Methodology is presented in section four. Data analysis and results are provided in section five, followed by the conclusion in the last section

2 Related Work

Technology is developing at such an accelerated pace that some jobs cease to exist during the period which elapses from the moment someone enrols at a university until he or she graduates. Moreover, there is a gap between technical skills acquired by education and needs of employers [4].

Efficient STEM education turned into an economic problem on a global level [5]. According to [6], the U.S. representative Martha Roby, R-Montgomery, claimed that almost 2.8 million of STEM-related jobs in 2018 were vacant mostly because STEM education, especially in rural areas, was unavailable to a great number of students. Labour market shows the fastest growing demand for experts in STEM. At the same time, according to the Ministry of Education in the U.S., only 16% of secondary school students express their interest in STEM. STEM jobs require a good understanding of Mathematics. However, many children do not accomplish satisfactory results in Mathematics. According to the National initiative for Mathematics and Science, only 36% of the U.S. secondary school students are willing to continue their university level education in STEM areas.

Since Mathematics forms the basis for other sciences and has a huge influence on economy and society in general [7], creative experts who have predispositions for success in science and technology could be detected through their education in Mathematics. It is important to detect those students who have the potential in Mathematics but have not yet decided on their future career. In that way, they could be guided into STEM area, considering the fact that Mathematics, besides being a constituent part of STEM, also forms the basis for better mastering of the remaining integral parts [8] including engineering. Students who choose STEM already in secondary schools, usually choose it on the university level as well [9], and they more and more often consider careers in entrepreneurship and innovations [10].

The knowledge of Mathematics is a key to mastering engineering studies [11]. Majority of engineering programs are based on STEM because they heavily depend on Mathematics and natural sciences [12].

E-learning is a form of distance learning which includes all the elements listed by the authors in [3] and which are needed for a successful implementation of STEM. However, for better efficiency, the design of the systems based on e-learning has to be carefully planned. One of the most important components in the design is related to the analysis of student needs and possibilities. It is necessary to consider all of the following: student motivation for learning, psychomotor skills, attitudes and ways of thinking, mental discipline, communication and social skills, talent and intelligence, learning styles, prior education and digital fluency, and the preferred learning medium. It is also important to consider external conditions of learning and to have control over applying the acquired knowledge [13].

M-learning complements e-learning with the possibility to use the system anywhere and anytime [14], and the possibility to learn while on the go. M-learning makes learning of Mathematics possible even in real-life situations in which the mobile device is used for navigating through real-life paths in which mathematical problems are solved [15]. Gamification methods can positively affect learning outcomes and they can be used in motivating students for STEM [16].

One of the major disadvantages of using computer games in the educational process is reflected in the fact that game development can be time-consuming and extremely financially exhaustive. Creating educational environment which includes learning through computer games is difficult for teachers who do not have any knowledge of programming, design, and animation. Additional problems of using games in education are posed by the difficulty to connect concepts from teaching materials to game mechanisms [17]. Besides studying motivation [18, 19], research studies in which computer games are used for learning primary school Mathematics also analyse the learning outcomes gained [20, 21]. In order to be successful, learning through computer games should include game elements and not just be a digital version of class exercises [22].

The goal of this research study is not only to evaluate the model of learning through computer games, but also to use interaction with the game for detecting students gifted in Mathematics. Individualized approach is ideal for accomplishing optimal results in educating gifted students, and information and communication technology (ICT) facilitates creating such environments [23].

According to the National Framework for Facilitating Learning Experience and Evaluating Accomplishments of Gifted Children and Students [24], there are several groups of area specific abilities in gifted children:

- Cognitive (gift for Mathematics, Physics, Chemistry, Technics, and Informatics – computer programming, electrical engineering, robotics, modelling, etc.),
- Artistic expression (gift for art, music, acting, literary expression, etc.),
- Psychomotor (gift for sport, dance and physical activities),
- Psychosocial (gift for leadership, self-revelation, etc.).

The intellectual characteristics most often observed in gifted students are the following:

- High level of general intelligence and particularly high level of a certain specific ability
- Highly developed ability of reasoning and logical thinking
- Highly developed ability of connecting information, recognizing relationships and patters
- Highly developed ability of solving problems
- Highly developed ability of abstract thinking
- Creativity / divergent thinking, originality, inventiveness
- The ability to reproduce numerous ideas
- Mental flexibility
- Fast learning
- Long and deep concentration ability
- Excellent memory
- Developed metacognition
- Intellectual curiosity
- Imaginativeness.

3 Research Questions

The goal of this research is to develop an educational model of early detection of gifted students with interest in STEM and particularly Mathematics. The model should be appropriate for primary school students who start learning the subject field of Mathematics, and it should be available simultaneously to a wide number of users. Additionally, besides being mobile-friendly, it should also contain motivational elements which would ensure its wide usage. With the aim to detect students gifted in Mathematics, by analysing results they accomplish in the computer game and by analysing their way of solving problem tasks, the following two null-hypotheses are formulated:

H1: there is no difference between students who take classes in additional Mathematics and other students regarding the accuracy in solving problem tasks in educational computer games,

H2: there is no difference between students who take classes in additional Mathematics and other students regarding the way they finish levels (game style which refers to the use of different elements for obtaining correct answers) in educational computer games in tasks in which there are multiple solutions.

4 Methodology

A model of mobile learning through computer games is developed for the purpose of this research. The aim is to facilitate learning of a content which requires the development of imagination and abstract thinking. Therefore, the game covers operations with Roman numerals.

Although Roman numerals do not have zero and they are usually used for labelling (e.g. clock, geometric planes, years in TV production), this research uses Roman numerals to define problem tasks for which the principle of obtaining solutions is provided in parallel to Arabic numerals in the game, as given in Fig. 1. These general instructions, which elaborate on how to calculate with Roman numerals, also serve as an auxiliary element for mastering levels of the game. Solving arithmetic tasks commonly implies making changes to numeric values [25], however, with Roman numerals the procedure also entails transposition or decomposition of numbers.

Fig. 1. Instructions and teaching materials in the game for learning arithmetic operations with Roman numerals

According to the way they can be solved, i.e. regarding the elements that need to be changed, problem tasks in the game developed for the purpose of this research can be divided into three groups: value (a numeric value), operator (symbol of an operator), and hybrid (a numeric value and symbol of an operator).

The types of tasks can be written in the following concise forms:

- a_1 k_1 a_2 k_2 a_3 (value, example: I + II = I, solution: I + I = II)
- a_1 o_1 a_2 o_2 a_3 (operator, example: I – III = II, solution: I = III – II)
- a_1 o a_2 k a_3 (hybrid, example: III – I = III, solution: II + I = III)

In the above given definitions, a stands for numeric values, o for operators (a and o can be changed), and k for constants. Regardless of whether a constant is a numeric value or an operator, it is not supposed to change while solving the task. More precisely, by changing it, it is not possible to obtain a correct answer.

According to the difficulty level, previous studies have shown that the easiest tasks are those in which a value needs to be changed (90% solvable). Hybrid tasks have proven to be 75% solvable, while the most difficult tasks are those in which the equality operator needs to be manipulated, and these can be successfully solved by 60% of students [26]. Operator type of tasks are more difficult to solve since both the constraints on values and operators are loosened, so there are more possibilities to consider. They give a different perspective to the problem, in which the solution can be obtained by changing an operator or the equal sign and often result in the “aha” effect [27].

The model does not impose the limit on the number of games played, it allows up to three wrong attempts per game, as well as different ways of solving problem tasks, and thus encourages students to experiment. If a task is solved correctly, the remaining time is added to the total score. This means that the student with the highest score is actually the fastest student. Besides providing basic functionality, the model includes different graphics, animations, top lists, collaboration between students, etc. Student interactions with different parts of the user interface and with the game itself are analysed separately. Interactivity helps in boosting accuracy of solving problem tasks with Roman numerals [28].

Different concepts and mechanisms need to be applied in order to achieve successful computer game-based learning. Concepts include intrinsic motivation, pleasure and fun, authenticity, self-confidence, autonomy, and experimenting [29]. The applied mechanisms are shown in Table 1.

Table 1. The mechanisms applied in learning through educational computer games

Mechanism	Application in the educational computer game for learning Mathematics
Rules	Given in instructions
Clear and challenging goals	The solution to a problem task needs to be provided within given time limits
Roles and phantasy	The introductory story, characters at the beginning and end of game, and when winning medals. Continuous display of characters at all levels with the aim to indulge, and encouragement while playing.
Progressive difficulty	Each level is more difficult than the previous one
Interaction	It is possible to experiment with answers. In each game, one is allowed to make at most three mistakes.
Insecurity and unpredictability	"Aha" type of task
Immediate and constructive feedback	The result visible after each move, the progress compared to other players, the comparison of top 20 results, winning trophies and medals
Exchange of experience	Dedicated social network

4.1 Definition of students gifted in Mathematics

When working with gifted students, additional attention is required related to the development of their abilities, the organization of special forms of teaching, competition preparations, etc. In this research, we have adopted the definition given by the subject matter teachers: students gifted in Mathematics are those students who are interested in Mathematics and who are successful in additional Mathematics classes. The curricula of additional Mathematics differ depending on the grade and classes are held on a weekly basis in the duration of two school hours per grade. Therefore, the educational game used in this research is designed in a way that the content it covers is not included in neither regular nor additional Mathematics curricula.

Although taking additional classes in Mathematics is a voluntary activity for which only those interested in the subject apply, teachers say that those who cannot follow this demanding program usually give up on their own after preliminary results. Preliminary results are obtained through preparations and through conducting different competitions. The expectations of the subject matter teachers are based on the assumption that the analysis of student interactions with the applied model in the domain of learning related to Roman numerals, and the analysis of outcomes (achievements) would enable detecting those who, besides being interested, would also be successful, which is a pre-requisite for STEM success.

4.2 The application of generic student competencies in the developed model

Generally speaking, the developed model is based on the Proposal of the National Curriculum Framework regarding the integration of generic competencies, which can and should be developed in children and young adults at all levels and in all types of education, all areas of curriculum, inter-subject topics, subjects, and modules within the education system of the Republic of Croatia [30]. The inter-relationships of these generic competencies, which are taken from the chapters "Modes of thinking" and "Forms of work and use of tools" on one hand, and their utilization in the model on the other hand, are given in Table 2.

Table 2. Relationships between generic competencies and their utilization in the model

Chapter	Generic competency	Utilization in the model
Modes of thinking	Problem solving	Problem tasks in games
	Decision making	Finishing levels by interacting with objects
	Metacognition	Modules: Show my progress Trophies and medals Top 20
	Critical thinking	Social network expression
	Creativity and innovativeness	Multiple ways of solving problem tasks
Forms of work and use of tools	Communication Collaboration	Social network
	Information literacy Digital literacy and use of technology	All elements and parts of user interface

4.3 Dataset

The dataset is collected during the interaction of students with the game "Zagonetke mudrog lisca" (Riddles of the Wise Fox), which has 15 pre-defined levels ordered by increasing difficulty. It involves problem tasks in Mathematics presented through Roman numerals, as shown in the instructions in Fig. 1. Each level presents an incorrectly formulated Roman numeral equation, which needs to be corrected by moving matchsticks used for representing both Roman numerals and mathematical operators. Some equations have multiple possible solutions, and matchsticks are movable no matter whether they represent Roman numerals or mathematical operators. Students have 50 seconds per level to solve a given problem. There is no randomization in the game, which means that restarting the game results in exactly the same tasks of exactly the same order.

Log-in is anonymized using nicknames which authorize students to use the system.

The research is conducted on the sample of 104 students attending grade 5-8 of a primary school in the Republic of Croatia. The students are between 11 and 14 years old and take classes in Mathematics. The time period covered refers to the academic year 2017/2018, and includes one week prior to winter holidays, three weeks of holidays, and two weeks after holidays. The system was accessed by 70.19% of students or 73 students in total. The detailed description of the dataset (the total number of students and the number of students who accessed the system per each grade with respect to whether they take additional classes in Mathematics) is given in Table 3.

Table 3. Description of the dataset

Grade	**Additional Mathematics**			
	Class Yes		***Class No***	
	Total	***Accessed***	***Total***	***Accessed***
5	10	8	14	9
6	6	6	26	19
7	3	3	19	10
8	4	4	22	14
Total	23	21	81	52

5 Data Analysis and Results

The number of times the game "Zagonetke mudrog lisca" was played with a final score different from zero, which includes all the games in which at least the first level was passed, is 2847 in total. The number of times the game was played and the percentage of students playing the game, differentiated by whether the students take additional classes in Mathematics, and the time period covered, is given in Table 4.

Table 4. Playing the game "Zagonetke mudrog lisca" grouped per time period

Additional Mathematics class	**Time period in relation to holidays**					
	Before		***During***		***After***	
	Number of times the game was played	***Average % of students***	***Number of times the game was played***	***Average % of students***	***Number of times the game was played***	***Average % of students***
YES	680	95.24 (20)	357	57.14 (12)	82	42.86 (9)
NO	1065	88.46 (46)	315	30.77 (16)	348	30.77 (16)

It can be observed that those who take just regular classes in Mathematics play the game in the periods when classes take place rather than during holidays, unlike those who take additional classes in Mathematics, i.e. without incentive from the school environment, the game is played by less students. The overall number of students who play the game is in favour of class NO because this class is more represented in the dataset but also because students belonging to that class are less successful in playing the game so they have to play all over again more often in order to get a new chance of solving the tasks.

It is evident that students during holidays relax. Since playing the game is a voluntary activity, a significant amount of those who do not take additional classes in Mathematics give up from playing the game during the holidays and do not ever go back playing. On the other hand, those who take additional classes in Mathematics are much faster in acquiring good results and better than those without these classes but they mostly play again only when someone beats their result.

Dependent on the difficulty, students could interact with a maximum of 15 elements at each level (Table 5).

Table 5. Elements used in finishing levels in the game "Zagonetke mudrog lisca" differentiated by whether the student takes additional classes in Mathematics

Level	Element for correct answer	Number of correct answers Additional Math class (Yes / No)				Total correct answers Class (Yes / No)	Incorrect answers Class (Yes / No)
2	1 || 2 || 8 || 9	14 / 22	448 / 383	527 / 949	57 / 163	1046 / 1517	364 / 741
3	1 || 2 || 3	81 / 101	67 / 68	812 / 1202	-	960 / 1371	245 / 471
4	4	927 / 1294	-	-	-	927 / 1294	99 / 229
5	6 || 7	241 / 110	617 / 1039	-	-	858 / 1149	178 / 373
6	5 || 6	780 / 994	46 / 94	-	-	826 / 1088	102 / 225
7	1 || 2 || 8 || 9	167 / 68	217 / 728	32 / 8	358 / 206	774 / 1010	148 / 201
8	3 || 10	350 / 492	376 / 465	-	-	726 / 957	141 / 166
9	4 || 5	510 / 834	186 / 68	-	-	696 / 902	72 / 162
10	3 || 4 || 5	1 / 2	8 / 4	656 / 850	-	665 / 856	94 / 152
11	6 || 7	220 / 90	425 / 721	-	-	645 / 811	41 / 115
12	5 || 6	100 / 9	521 / 753	-	-	621 / 762	50 / 141
13	13	610 / 741	-	-	-	610 / 741	34 / 62
14	4	572 / 678	-	-	-	572 / 678	94 / 146
15	4	562 / 665	-	-	-	562 / 665	35 / 42

In most cases the same element can be used for getting both correct and incorrect answer (depended on the area of use, i.e. whether the element is dropped on the area taken up by a correct answer or somewhere else), although at some levels correct answer can be obtained by using up to four different elements.

On average, students make more mistakes at beginner levels while still not having learned the problem-solving strategy (up to and including level 5 which has the "Aha!" type of task) as shown in Fig. 2. Considering higher levels (over 10), they mostly have difficulties with level 14, which is the only level with the type of task including three values on the left side of the equation, which is solved by moving elements of arithmetic operators in order to change the values.

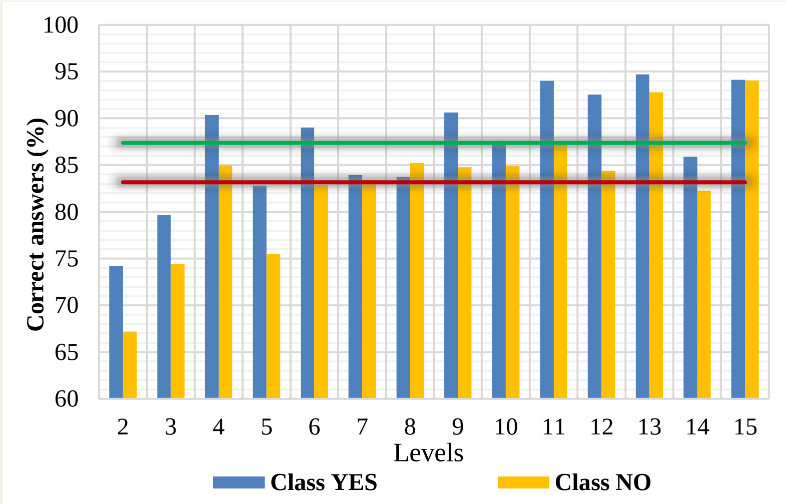

Fig. 2. Accuracy in solving the tasks for students taking additional classes in Mathematics (class YES) and those taking regular classes only (class NO) in the game "Zagonetke mudrog lisca"

Students who take additional classes in Mathematics have an average accuracy of 87.38%, while those who take only regular classes have an average accuracy of 83.16%. Fig. 3 shows a heat map related to the difficulty of solving problems at a certain level differentiated by the additional Mathematics.

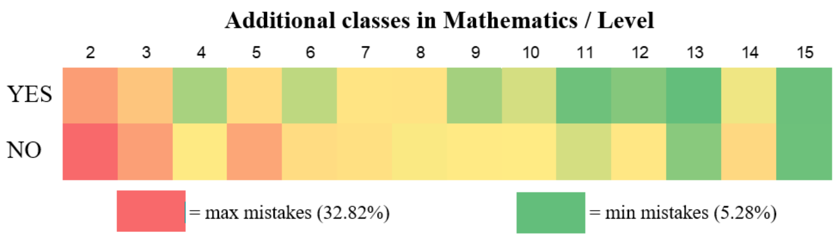

Fig. 3. Difficulty of game levels differentiated by whether students take additional classes in Mathematics in the game "Zagonetke mudrog lisca"

The map is a relative indicator of the number of incorrect answers with regard to the total number of answers at that level. It shows levels at which students make more mistakes or less mistakes with regard to whether they take additional classes in Mathematics. It is evident that students who take additional classes in Mathematics achieve better average results than other students do at all levels except for one. The result is statistically significant according to the statistical chi-square test ($\chi 2$ = 17.2857, $p < .05$). The null-hypothesis H1 is rejected because the difference in accuracy between students who take additional classes in Mathematics and other students regarding solving problem tasks in educational computer games is significant.

Average results (scores) differentiated by whether students take additional classes in Mathematics (YES: 4745.54; NO: 4188.81) also speak in favour of the obtained results, as well as the average number of levels passed by students in the game (YES: 10.76; NO: 9.55), as given in Fig. 4.

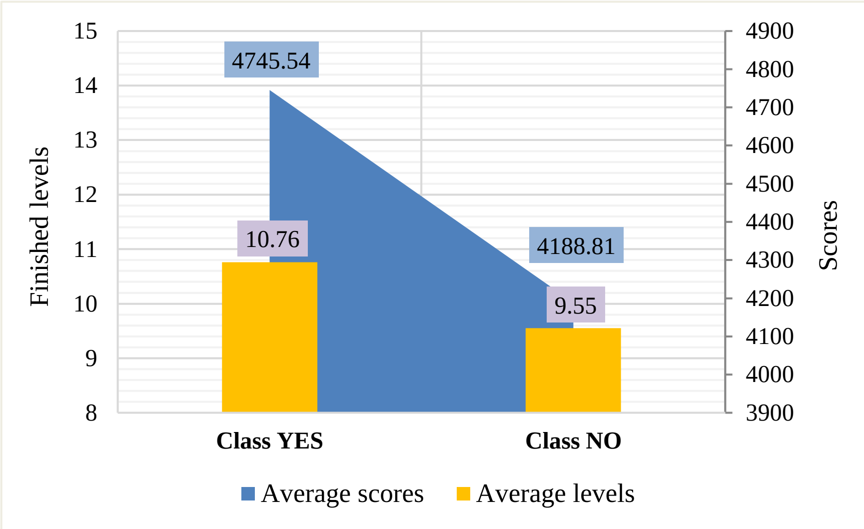

Fig. 4. Average scores and finished levels in the game "Zagonetke mudrog lisca" differentiated by whether students take additional classes in Mathematics

Ten levels have multiple solutions. The chi-square test shows that a statistically significant difference ($p < .05$) exists in the ways of solving tasks between students who take additional classes in Mathematics and other students for six of these levels (2, 5, 7, 9, 11, and 12).

Students who take additional classes in Mathematics solve tasks with multiple solutions in more than one way (they use different elements for obtaining correct solutions), i.e. they experiment in getting the right answer more than other students, who mostly use the same elements to get to the correct solution. The null-hypothesis H2 is, therefore, rejected, and the working hypothesis is accepted: there is a difference between students who take additional classes in Mathematics and other students in the ways of finishing levels (game style which refers to the use of different elements for obtaining correct answers) of educational computer games which contain multiple solutions.

The instructions are accessed 150 times, 81 time by 15 students who take additional classes in Mathematics (on average 5.4 per student), and 69 times by 22 students who take only regular classes (on average 3.14 per student). Not all the students looked up instructions. Based on the averages, it can be concluded that students who take additional classes in Mathematics use instructions more than other students, which can help them in solving problem tasks. This probably shows their proneness to approach the problem comprehensively, and to be meticulous rather than careless.

6 Conclusion and Future Work

By analysing different criteria for success, it has been shown that students gifted in Mathematics have expectedly higher accuracy in finishing levels of educational computer games. However, it has also been shown that gifted students exhibit different cognitive styles in educational computer games, i.e. they use game elements differently from other students with the aim to gain multiple solutions if possible.

In line with the research goal, the analysis reveals that predictive models can be built in order to detect students gifted in Mathematics. Besides being interested in Mathematics, i.e. STEM area, which is evident from voluntarily applying for additional classes in Mathematics, it needs to be determined whether these students have predispositions for following this more advanced form of teaching. By the implemented predictive models it is possible to pre-select students in order to determine whether they are gifted in Mathematics. The preselection is based on success, which is measured by different features of the applied educational game and student scores.

Since the mobile learning model is based on generic competencies, it can be used in curricula of other subjects by simply replacing the domain of teaching with other primary or secondary school content of the subject matter curricula of other STEM constituents.

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