Innovative pedagogies and personalisation in STEM education with NEWTON Atomic Structure Virtual Lab

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Abstract: STEM education in Europe is suffering due to student disengagement and demotivation, which is starting as early as 12-13 years of age. STEM education should be student-centred, encouraging inquiry and problem-solving skills, while being personalised for each student. Practical training is becoming a challenge for schools and universities due to funding cuts and space limitations. Virtual labs provide a solution to these challenges by removing limitations set by time, equipment, and geography. This paper presents the Atomic Structure Virtual Lab aimed at teaching secondary level Chemistry students, developed as a part of the EU H2020 NEWTON Project. This virtual lab is based on inquiry-based and self-directed learning, placing the students at the centre of the learning experience. The lab incorporates personalisation in the form of an innovative learning loop, gamification elements, instant feedback, accessibility for the hearing impaired, providing a unique learning experience for students. Preliminary interviews with secondary school students and teachers showed positive aspects and benefits of the Atomic Structure Virtual Lab.

Introduction

The disengagement of European students from science is apparent, causing Europe to face a shortage of skilled scientists in the future. However, there are two recognised key factors that can be tackled. Students consider scientific subjects too difficult to pursue, and are uncertain about how interesting and promising the career paths available for STEM graduates really are (Playfoot, 2016). These attitudes lead to lack of motivation and make STEM subjects seem irrelevant to students. Furthermore, we do not teach in a way that is suitable for the millennials, who are digital natives, use technology every day in their lives and believe it should be integrated into education. Many educational institutions also suffer from lack of funding and resources (e.g., time, lab space, equipment), and struggle to provide their students with sufficient practical training, despite practical experiments being a key part of STEM education, with students required to learn essential lab skills throughout their schooling and degrees (Wolf, 2010; Abdulwahed, 2010). Reducing the teaching of STEM subjects to lectures instead of lab work is highly unlikely to increase the already-withering motivation in students. Virtual labs remove the limitations set by time and geography, enable personalisation of content (Fernández-Avilés, Dotor, Contreras, & Salazar, 2016), instant feedback and automated corrections, hence making the teaching and learning experience more enjoyable for both students and teachers. Multimedia approach, combined with personalised inquiry-based exercises that allow students to learn analytical and research skills, question and practise at their own pace, are one of the benefits of virtual labs.

NEWTON Project[1], as a part of European Union's Horizon 2020 Research and Innovation programme, is currently developing and piloting virtual labs to revolutionise the way STEM subjects are taught throughout European schools and colleges (Bogusevschi, Tal, et al., 2018; Bogusevschi, Bratu, Ghergulescu, Muntean, & Muntean, 2018). Irish Science teachers were interviewed and filled in a questionnaire about virtual labs, and the Atomic Virtual Lab was developed by taking into account the teacher needs and challenges as per the results of the survey (Lynch & Ghergulescu, 2017a). The Atomic Structure Virtual Lab, which has been developed as part of the NEWTON Project, teaches secondary level Chemistry students about the structure of atoms, their isotopes and how they form bonds to form molecules. This virtual lab is based on student-centred, inquiry-based and personalised pedagogies. The gamification elements and inquiry-based exercises of Atomic Structure make the virtual lab fun and engaging, while different levels of difficulty provide each student with the most suitable level of challenge. Through self-directed learning, students are encouraged to think about and take responsibility for their own learning, as well as to take on

[1] http://www.newtonproject.eu/

an active role rather than that of a passive listener. The personalised feedback provides students with correct answers to questions they may get wrong and encourages students on their learning journey.

This rest of the paper is structured as follows: section 2 presents a review of existing virtual labs and their pedagogies, section 3 presents the Atomic Structure Virtual Lab and its innovative pedagogies and personalisation layers, section 4 presents preliminary results, while section 5 concludes the paper and presents future work directions.

Literature review

There are several virtual labs available for educators to utilise in STEM education, many of which were reviewed by Lynch & Ghergulescu (2017b). Many of these utilise multimedia material, virtual experiments and/or simulation-based exercises, such as the Go-Lab Project (de Jong, Sotiriou, & Gillet, 2014) and GridLabUPM (Fernández-Avilés et al., 2016). As technology advances and millennials have taken to video games and online gaming, the use of avatars in education has grown in popularity. Virtual worlds such as Second Life already host several virtual labs, as studied in e.g. (August et al., 2016) and (Keeney-Kennicutt & Winkelmann, 2013). Keeney-Kennicutt & Winkelmann (2013) found that students performed better in the virtual world than in a traditional lab. Similarly, Shapira, Amores, & Benavides (2016) reported that students learnt quicker in a virtual lab with tangible objects than in a traditional lab, or in a virtual lab with non-tangible objects. Students have found one of the primary benefits of virtual labs the possibility to carry the experiment countless of times. Furthermore, the absence of real hazards allows students to concentrate on the task at hand, thus providing a better learning experience (Wolf, 2010), and in general, user feedback on learning in the virtual world has been notably positive.

However, some criticism for virtual labs states that if the virtual lab design and implementation is not carried out correctly, this leads to over-simplifying of the concept at hand, resulting in an unrealistic lab experience (Culbertson & Kuchenbecker, 2017), and in some experiments there is a risk of disregarding health and safety in the lab environment (Keeney-Kennicutt & Winkelmann, 2013). Unfortunately, special education has been neglected in most of the existing virtual labs (Lynch & Ghergulescu, 2017b), even though special education needs students can hugely benefit from learning online (Baladoh, Elgamal, & Abas, 2016). This lack of accessibility exists despite several studies reporting that utilising virtual reality, augmented reality and multisensorial activities improve the quality of special education needs students' learning (Baladoh et al., 2016; Im & Kim, 2014; Zarfaty, Nunes, & Bryant, 2004). Virtual labs enable the implementation of different types of activities, from using videos and audio for students who learn best by watching and listening to interactive exercises to catering for those who learn best empirically. Many existing virtual labs, however, fail to cater for different learners. Furthermore, personalisation and adaptation, which are recognised as a key feature of future pedagogies, are missing from most existing virtual labs (Lynch & Ghergulescu, 2017b). Though many offer inquiry-based exercises, these are not personalised to the students' individual skills and requirements.

Atomic Structure Virtual Lab

The Atomic Structure Virtual Lab places the student in the centre of the learning experience through implementation of personalisation, inquiry-based learning, and self-directed learning. These innovative pedagogies are widely recognised as being beneficial as students learn to carry out their own experiments, analyse and question, and take responsibility for their own learning (Wang, Guo, & Jou, 2015). Most importantly, personalisation makes the learning experience an individual one, as one size does not fit all in education (Docebo, 2017). These pedagogies, combined with interactive activities and the use of multimedia, make the Atomic Structure Virtual Lab an engaging, encouraging, and fun learning environment. In the lab students are active participants, not passive listeners: they are in charge of their own learning. Personalisation in this virtual lab is implemented at different levels throughout the entire learning journey. The levels of personalisation are presented in more detail below:

- Learning Loop-based personalisation
- Feedback-based personalisation
- Innovative pedagogies-based personalisation (inquiry-based learning and self-directed learning)
- Gamification-based personalisation
- Special Needs-based personalisation (for hearing impaired students)

Learning Loop-based Personalisation in the Atomic Structure Virtual Lab

Learners progress through the five phases of a novel learning loop in the Atomic Structure Virtual Lab (see Figure 1 and Figure 2).

1. *Readiness*: making sure the learner acquired the necessary background skills and knowledge to start a new learning experience session.
2. *Preparation*: arousing interest - suggesting the learners what they could learn and linking with the natural phenomenon.
3. *Presentation*: Encountering the New knowledge or Skills - coaching the learner through what and how to learn.
4. *Practice*: Integrating the new knowledge or skills - engaging the learner with a personalised and prompt progress feedback and gamification mechanics.
5. *Performance through Inquiry-based Learning*: Applying the new knowledge and skills – leading the learner to go further and deeper into the material to be learned.

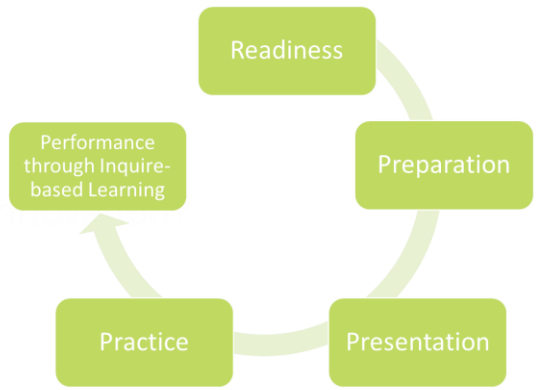

Figure 1. Atomic Structure Virtual Lab innovative 5-phase learning loop.

These phases of the learning loop will ensure that the student progresses at a pace that is suitable for them, while offering new challenges along the learning path, but without overwhelming the student. Hence, the first phase, Readiness, determines whether there are any prerequisites for this lab. The second phase, Preparation, is designed to arouse the student’s interest about the topic at hand, but also to create a link between the natural phenomenon or process, and the lab experiment. Making a topic relevant to the students assists comprehension and learning and increases motivation. The third phase, Presentation, shows students how to learn, as well as reminds them what they are learning about. Here, some students have already understood the basic concepts and are ready to embrace independent learning, while some still require a bit more direction and assistance. By offering students different levels of difficulty, as part of the implementation of adaptation and personalisation, students get to proceed at their own level and pace. The fourth phase, Practise, is where students get to practise their newly learned skill, and the fifth stage, Performance through Inquiry-based Learning, is where they are provided with a challenge and they get to apply their skills and knowledge to their best ability through inquiry-based learning.

Furthermore, a learning path with three stages is included in the Atomic Structure virtual lab: (1) Atoms, (2) Isotopes, and (3) Molecules. The five phases of learning are incorporated into each of the stages, and the student is required to proceed through these stages in order (Figure 2). A student cannot, for instance, start with the Molecule part of the virtual lab, as they do not fill the prerequisites until they have studied Atoms and Isotopes. The continuity of the phases should become familiar to the students and assist them with their learning throughout the learning experience. Furthermore, by discouraging students from studying topics they are not ready for, this five-phase learning loop should minimise the formation of misconceptions.

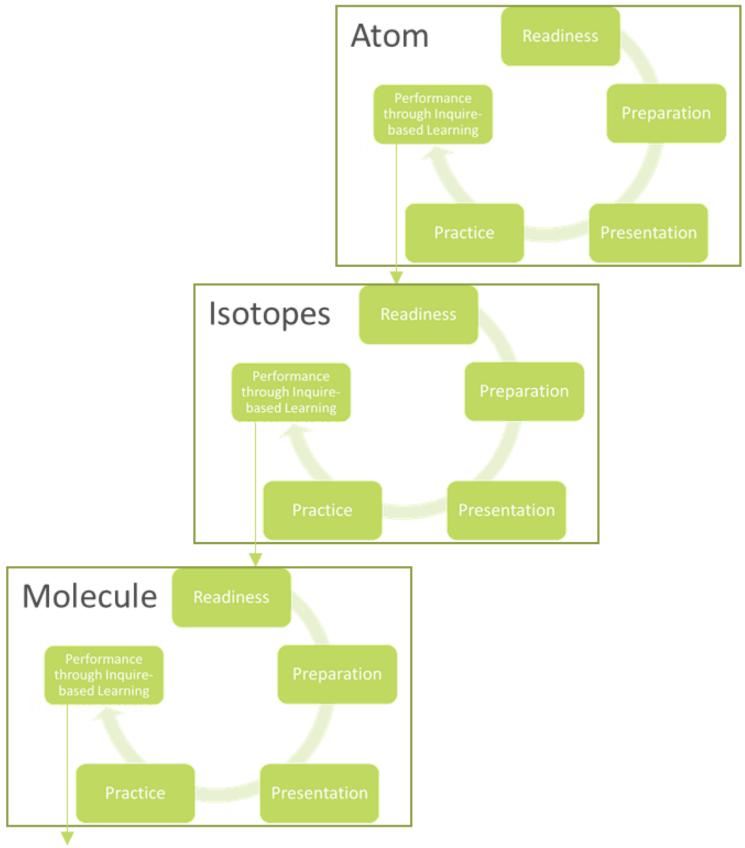

Figure 2. In the Atomic Structure Virtual Lab, students must unlock the next stage by progressing through 1) Atoms, 2) Isotopes and 3) Molecules. The five-phase learning loop is included in all three stages.

Feedback-based Personalisation in the Atomic Structure Virtual Lab

Students will receive instant feedback as they work through the exercises and have a chance to review what they did not learn directly after the exercise. This keeps them focused on the concept, and helps prevent misconceptions about scientific concepts, which can be more difficult to eradicate at a later stage. There are three feedback types: correct answers, feedback on correct solution and guided self-directed learning. For example, if a student has little faith in their own skills in the self-directed learning quiz, they receive a message saying: “Don’t worry, we’ll be helping you along the way.” If a student scores high in the same quiz, the message says: “Looks like you are an explorer, this next task is just for you!”. After answering up to 6 multiple-choice and closed-ended questions, the student is provided with feedback on not only the correct answers, but also a recommendation if the system thinks they would benefit from taking the quiz again: “You remembered some bits, maybe have another crack at it?” Student also get positive feedback on task completion as well as fun facts (see Figure 3).

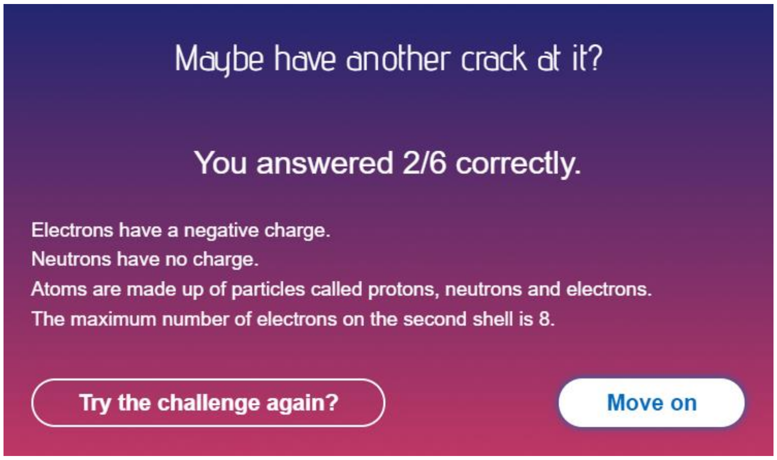

Figure 3a. Feedback for a student after a mini-quiz.

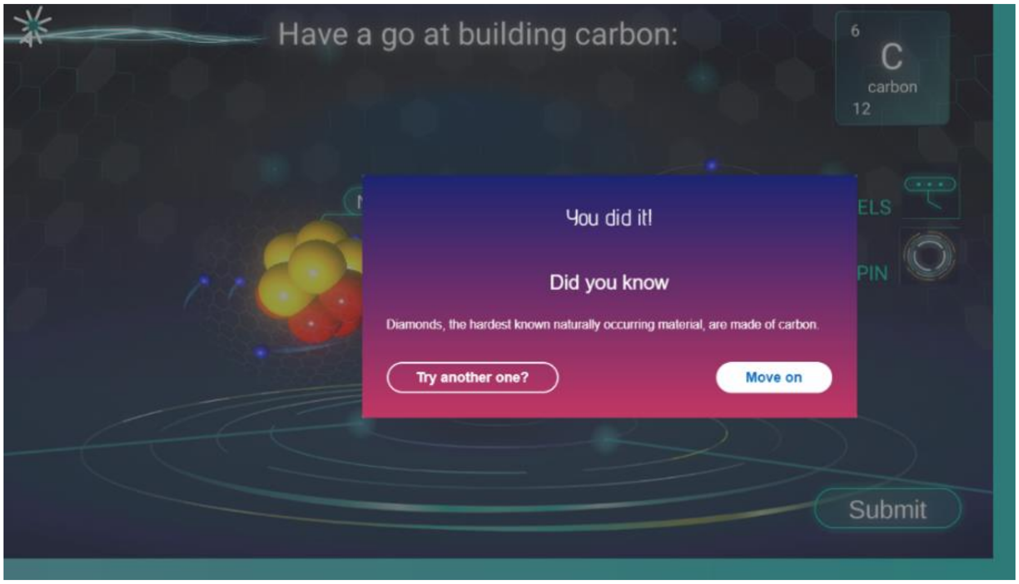

Figure 3b. Student gets feedback and a fun fact about the element s/he has built.

Innovative pedagogy-based Personalisation in the Atomic Structure Virtual Lab

Inquiry-Based learning (IBL) and Self-Directed Learning (SDL) have been shown to improve the students' learning outcomes, motivation, and confidence. As the goal of the NEWTON project is to prevent the disengagement of students, especially girls, from STEM education, and to change the way we teach science, these pedagogies are deemed the most suitable for Atomic Structure Virtual Lab. Students' levels of SDL and Self-Efficacy (SE) are assessed at the beginning of the virtual lab through a short questionnaire. This questionnaire should also function as a tool to help students focus on what they are about to do in the virtual lab and make them consider their own learning and take responsibility for it. Considering one's learning is a step on the way to lifelong learning. In this virtual lab, personalisation is implemented as different types of feedback and levels of guidance provided through the entire lab. The difficulty level is also personalised based on the students' levels of SDL, SE and performance through the lab. Students who struggle with the basic definitions and/or score low in the self-efficacy test will be directed through the virtual lab one stage at a time and will be given the simplest structures to build in the inquiry-based learning sections, where students are invited to build certain atoms, isotopes and molecules. Students with high SDL, SE and good performance are catered for by letting them proceed through the lab independently, and more ambitious and motivated students will be offered more complex atoms and isotopes where to choose from (Figure 4). Students carry out mini-quizzes throughout the labs to keep their mind focused on the new information they have acquired. These short quizzes appear after each stage, and function also to ensure that the student stays aware of the learning objectives, as these form the basis of the quizzes. There are three different levels of difficulty in the quizzes, determined by the student's level of SDL and SE.

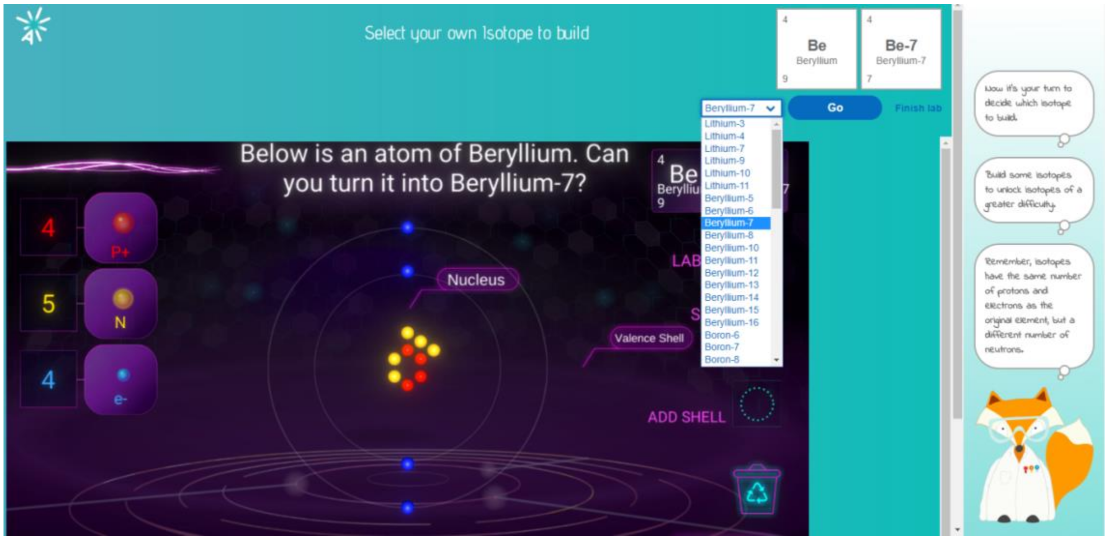

Figure 4. Illustration of Building an Isotope of Beryllium in Inquiry-based Learning phase.

Gamification-based personalisation

Gamification-based personalisation, especially when students are playing alone rather than as a group, have been found to have a positive impact on learning (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014; Lynch et al., 2018). Gamification-based personalisation includes a focus on user-centeredness, similarly to inquiry-based learning and self-directed learning (Playfoot, 2016). In the Atomic Structure Virtual Lab, students earn badges for finishing a stage, and thus unlocking the next stage. The first stage is Atoms, second is Isotopes, and the third and final stage is Molecules. Students cannot proceed to the subsequent stage without unlocking the previous stage, as the previous stage includes the learning objective pre-requisites that the students must understand in the higher stages. Once a student finishes a stage and has earned a badge, s/he is given the option to either carry on at that level, or move on to the next.

Figure 5. Examples of badges given to students as they finish a stage in the Atomic Structure lab.

Special education needs – based personalisation in the Atomic Structure Virtual Lab

In the Atomic Structure Virtual Lab, Special needs-based personalisation addresses the requirements for hearing impaired students. Students have the option to choose sign language for the hearing impaired, and they will have a translator signing on screen as the audio is being played, to help make the abstract concepts become less vague and more concrete (Passig & Eden, 2000). It is important that the disability access (in this case the video) can be switched on or off depending on user model profile. Making the virtual lab accessible improves the special education needs students' achievement and practical skills (Baladoh et al., 2016), and provides students with the same learning opportunity as non-special education needs students.

Figure 6. Video in the Atomic Structure virtual lab with a sign language interpreter for hearing impaired students.

Preliminary Results

Both teachers and students were interviewed after interacting with the Atomic Structure Virtual Lab. The focus of the interviews with teachers were on identifying how the virtual lab is perceived from teacher perspective, what are the benefits of each novel personalisation layer integrated in the virtual lab, identifying if the virtual lab is aligned with the given learning objective as well as identifying how the virtual lab might impact students from teacher's point of view. Teachers acknowledged that "*Students can learn at their own pace and motivated students can assess themselves beyond the scope of the course.*" The teachers' perception was the learning loop "*creates a scaffolding for students to grow in confidence, assess their basic understanding and then challenging that understanding in applied circumstances*", while the inquiry-based learning aspect *"removes the passive element of the traditional classroom, and makes each student an agent of their own learning process, with responsibility for their own progress."* Personalisation was found beneficial as well as*" students learn at different rates and find different approaches more successful.".* The option for sign language instead of audio, for students with hearing impairments was welcomed. Teachers think that students will see them as "*a new and modern way of learning that it will increase their wish to learn Chemistry in a fun way*."

Students mentioned that they "*felt really positive about learning atomic structure with NEWTON Virtual Lab*" and that they "*enjoyed learning atomic structure with NEWTON Virtual Lab".* When asked what they liked about the learning activities from the NEWTON Atomic Structure the students mentioned that: "*it saves time*", "*it is easily to learn*", "*it makes students feel interesting for studying*", "*it is very good, it is truly helpful to students*", "*it makes students feel interest for studying*", "*really liked to do own learning. By the end I can do it by myself. I understood it more when I got to choose myself. It really helps*".

The Atomic Structure Virtual Lab will be piloted in Irish and Italian secondary schools in 2018. The pilot study will investigate the impact of the virtual lab to knowledge gain, motivation and affective state as well as perceptions towards STEM subjects. The impact of the virtual lab will be analysed in contrast with traditional approaches by using an experimental and a control group.

Conclusion and Future Work

This paper presented the Atomic Structure Virtual Lab developed as a part of the EU H2020 NEWTON Project. Using this virtual lab, students can learn the components and functions of atoms and isotopes, and how atoms bond to form molecules. Through active inquiry-based exercises, students get to explore the structure of atoms, isotopes and molecules. The multimedia visualisation and 3D model of the atomic and molecule structures help students to understand the abstract concepts that can be difficult to explain, as they cannot be explored in a traditional lab. The self-directed learning helps students to think about their own abilities and learning, helping especially those students who may lack confidence in their own skills. Personalisation, which is implemented at different levels throughout the learning journey, ensures that students who need more encouragement, receive it along the way, and students who are ready for independent study are offered the correct amount of challenge. The type of knowledge taught in this virtual lab is what will be tested in the students' final exams, and learning objectives are aligned with the national Science curriculum. Feedback from Science teachers has been remarkably positive, as they recognise the value of personalisation to cater for the needs of different types of learners, and inquiry-based learning and self-directed learning in teaching students analytical and problem-solving skills.

The Atomic Structure Virtual Lab will be piloted in Irish and Italian secondary school in February 2018 following the methodology presented by Montandon et al., (2018). The pilot study will include both objective and subjective measurements. A control group will learn the same concepts about atoms, isotopes and molecules, without the help of the virtual lab. Both the experimental group and the control group will carry out pre and post-testing to assess student's knowledge gain, and whether differences exist between the two groups. For the subjective measurements and user experience, interviews and focus groups with students and teachers will be carried out.

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