Atomic Structure Interactive Personalised Virtual Lab: Results from an Evaluation Study in Secondary Schools

Ioana Ghergulescu[1][a], Arghir-Nicolae Moldovan[2][b], Cristina Hava Muntean[2][c] and Gabriel-Miro Muntean[3][d]

[1]*Adaptemy, Dublin, Ireland*

[2]*School of Computing, National College of Ireland, Dublin, Ireland*

[3]*School of Electronic Engineering, Dublin City University, Dublin, Ireland*

ioana.ghergulescu@adaptemy.com, arghir.moldovan@ncirl.ie, cristina.muntean@ncirl.ie, gabriel.muntean@dcu.ie

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Abstract: Virtual labs are increasingly used both as an alternative to physical labs or as a complementary technology enhanced (TEL) solution for STEM education. Virtual labs enable students to conduct experiments in a controlled environment at their own pace. However, despite much research on personalisation and adaptation in the TEL area, most virtual labs that have been developed lack personalisation features. This paper presents results from a study with 78 secondary school students, aimed at evaluating an interactive personalised virtual lab called Atomic Structure. The virtual lab integrates personalisation, interactive experimentation, videos, e-assessment and gamification, to provide an engaging environment for learning chemistry concepts related to atoms, isotopes and molecules. The evaluation study followed a multi-dimensional methodology to assess the effectiveness of the virtual lab in terms of knowledge achievement, learner motivation and usability. The results show that the experimental group that learned with the virtual lab achieved statistically significant higher knowledge than the control group that attended a traditional teacher led session. The experimental group also had higher increase than the control group for different motivation dimensions between the pre and post questionnaires. The usability results showed that most students found the virtual lab useful, easy to use and liked/loved its features such as videos, quizzes and interactive atom builder.

1 INTRODUCTION

According to many research and government studies, there is an ongoing concern related to the low and decreasing engagement with STEM (Science, Technology, Engineering and Maths) education as students are progressing from primary to secondary to tertiary level (Howard, 2017; Milner-Bolotin, 2018; Patall, Hooper, Vasquez, Pituch, & Steingut, 2018). Addressing this issue is of major interest given the growing need for STEM employees to support technological innovation and economic growth (European Comission, 2016; OECD, 2015).

The lack of interest in STEM subjects is very complex and often students lose interest at a too early stage due to various contributing factors including perceived difficulty of STEM subjects (Patall et al., 2018; Shirazi, 2017), negative images of the field and negative ability and self-efficacy beliefs (van Aalderen-Smeets & van der Molen, 2018; van Tuijl & van der Molen, 2016). Among the factors that were identified to address the issue include adaptive and personalised learning which was shown to positively corelate with science performance even on country level data (Mostafa, Echazarra, & Guillou, 2018), inquire-based learning (Howard, 2017), and remote fab labs and virtual labs (Potkonjak et al., 2016).

The NEWTON Project (http://newtonproject.eu) is a large scale EU H2020 innovation action project that focuses on employing novel technologies in STEM education in order to increase learner quality of experience, improve learning process and increase

[a] https://orcid.org/0000-0003-3099-4221
[b] https://orcid.org/0000-0003-4151-1432
[c] https://orcid.org/0000-0001-5082-9253
[d] https://orcid.org/0000-0002-9332-4770

learning outcomes. Innovative technologies include Augmented Reality and Virtual Reality (D. Bogusevschi et al., 2018), virtual teaching and learning laboratory (Diana Bogusevschi, Muntean, & Muntean, 2019), remote fabrication labs (Togou, Lorenzo, Lorenzo, Cornetta, & Muntean, 2018), adaptive and personalised multimedia and multiple sensorial media (Bi et al., 2018; Moldovan, Ghergulescu, & Muntean, 2016), user modelling and personalisation (Mawas, Ghergulescu, Moldovan, & Muntean, 2018) and interactive educational computer-based video games (Mawas, Tal, et al., 2018). Different innovative pedagogical approaches are also deployed as part of the STEM teaching and learning process such as flipped classroom, game-based and problem-based learning (Chis, Moldovan, Murphy, Pathak, & Muntean, 2018; Muntean, El Mawas, Bradford, & Pathak, 2018; Zhao, Chis, Muntean, & Muntean, 2018).

Virtual labs in particular, have been proposed as one solution to overcome the costs associated with traditional labs that are resource intensive and costly to maintain for schools, as well as a solution to make practical science education available to online learners (Lynch & Ghergulescu, 2017a, 2017b). The goal of a virtual lab is to enable students to create and analyse their own experiments as well as to repeat them multiple times at their own pace. However, despite many studies showing the benefits of adaptive and personalised learning in both classroom and online settings, most virtual labs for STEM education lack personalisation features. Furthermore, there is a limited number of comprehensive case studies and experiments that evaluated the virtual labs in terms of their impact on learner motivation aspects such as engagement, interest and self-efficacy.

In this context, this paper presents the results of a study performed in an Irish school involving secondary school students. The study's goal was to evaluate an interactive personalised virtual lab called Atomic Structure. The 78 students that participated in the study were divided in two groups: an experimental group that learned following interaction with the Atomic Structure virtual lab and a control group that attended a traditional teacher led session. The research study followed a multidimensional methodology that applied knowledge tests and surveys before and after the learning session in order to comprehensively assess the impact of the Atomic Structure virtual lab on learners' knowledge, motivation and usability.

The rest of the paper is organized as follows. Section 2 discusses recent related works on virtual labs. Section 3 overviews the Atomic Structure virtual lab. Section 4 presents the research methodology for the evaluation study. Section 5 presents the results analysis. Section 6 discusses the main findings and limitations of the study and concludes the paper.

2 RELATED WORK

While many virtual labs were developed over the years, most of them targeted third-level education rather than secondary school education, although universities typically have more resources and better physical laboratories and equipment. Moreover, this is despite the fact that learners' disengagement from the STEM area starts during secondary level education in many countries when students start choosing which subjects they wish to pursue (Bøe & Henriksen, 2015; van Aalderen-Smeets & van der Molen, 2018).

Table 1 presents a summary of some existing virtual labs and platforms. Several European projects have focused on virtual labs. The Go-Lab project (de Jong, Sotiriou, & Gillet, 2014) has created a platform that enables educators to host and share with other users virtual labs, apps and inquiry learning spaces. The VccSSe project (Gorghiu, 2009) created a virtual community collaborating space for science education that provided virtual labs and training materials in physical laws including simulation-based exercises. The GridLabUPM (Fernández-Avilés, Dotor, Contreras, & Salazar, 2016) platform hosts a number of virtual laboratories that offers students practical experiences in the fields of electronics, chemistry, physics and topography. The BioInteractive (HHMI, n.d.) platform provides science education resources including activities, videos and interactive media (i.e., virtual labs, click & learn, interactive videos, 3D models, short courses). Other virtual labs / platforms include the Gizmos mathematics and science simulations (ExploreLearning, n.d.), Chemistry Lab and Wind Energy Lab (Migkotzidis et al., 2018), ChemCollective (Yaron, Karabinos, Lange, Greeno, & Leinhardt, 2010), Open Source Physics (Christian, Esquembre, & Barbato, 2011), and Labster (Stauffer, Gardner, Ungu, López-Córdoba, & Heim, 2018).

Most of these virtual labs offer simulation-based exercises, interactive activities and online tutorials to assist the student in their learning journey. The online tutorials and the multimedia educational resources are suitable to present the theoretical aspects, while the interactive activities and simulation-based exercises are important in achieving the practical skills and in understanding the phenomena / concepts. While virtual labs offer students a chance to practice their

Table 1: Summary of existing virtual labs and platforms.

Virtual Lab / Platform Name	Activities and Learning Materials	Adaptation and Personalisation
The Go-Lab Project (de Jong, Sotiriou and Gillet, 2014)	Multimedia material, Interactive learning activities	Gamification, Internationalisation, Inquiry Learning Spaces
Open Source Physics (Christian, Esquembre and Barbato, 2011)	Chat, email, virtual reality	N/A
VccSSe (Gorghiu, 2009)	Interactive learning activities	N/A
Bio Interactive (HHMI, n.d.)	Activities, videos, interactive media	N/A
Gizmos (ExploreLearning, n.d.)	Interactive simulations	N/A
Chemistry Lab, Wind Energy Lab (Migkotzidis *et al.*, 2018)	Mini-games	Difficulty adjustment
ChemCollective (Yaron *et al.*, 2010)	Interactive learning activities	N/A
Labster (Stauffer *et al.*, 2018)	Simulations-based exercises	N/A

all-important practical skills in a safe environment, most virtual labs lack personalization and adaptation features, and neglect inclusive education. Many virtual labs have also been criticised for over simplification of experiments, with the result that students do not learn all the necessary skills associated with specific exercises.

A number of research studies have conducted evaluation studies of virtual labs. Aljuhani *et al.* (2018) evaluated a chemistry virtual lab in terms of usability and knowledge improvement. The virtual lab was found to be an exciting, useful, and enjoyable learning environment during user trials. The main drawbacks of their study were the low number of participants and the lack of control and experimental group.

Migkotzidis *et al.* (2018) evaluated the Chemistry and the Wind Energy Lab in terms of usability, adoption, and engagement with the virtual labs. The participants expressed a positive opinion regarding the virtual lab interface and high engagement rates.

Bogusevschi *et al.* (2018) evaluated a virtual lab with 52 secondary school students in terms of learning effectiveness. The results had shown a statistically significant improvement in the experimental group using the virtual lab as compared to the control group learning using classic teacher-based approach.

Bellou, Papachristos and Mikropoulos (2018) did a systematic review of empirical research on digital learning technologies and secondary Chemistry education. The results of the review of 43 studies had shown that the researchers were mainly interested in the chemistry topics and to use digital learning technologies for visualisation and simulations but not in personalising the learning journey.

Despite much research and development in the area, there still is a lack of personalised virtual labs and a need for more comprehensive evaluation studies that look at the impact of virtual labs from multiple dimensions such as learner knowledge, motivation and usability. This study contributes to the area of research through a comprehensive multidimensional evaluation study of the Atomic Structure interactive personalised virtual lab with secondary school students.

3 ATOMIC STRUCTURE

Atomic Structure is an interactive personalised virtual lab for secondary levels students, that teaches abstract scientific concepts such as the structure of atoms, bonding of molecules, gaining and losing electrons, that can be hard for students to grasp, and difficult for teachers to present with traditional teaching materials (Ghergulescu et al., 2018; Lynch & Ghergulescu, 2018). The Atomic Structure virtual lab places the student in the centre of the learning experience by implementing personalisation at various layers.

The pedagogical foundations of this virtual lab are self-directed learning, learning in flow, and inquiry-based learning. These innovative pedagogies are beneficial for enabling learners to carry out their own experiments, analyse and question, and take responsibility for their own learning (Wang, Guo, & Jou, 2015), while personalisation makes the learning experience an individual one and keeps the learner engaged.

Figure 1 shows the models built into the Atomic Structure virtual lab to enable personalisation and adaptation. The virtual lab covers concepts such as: atoms, isotopes and molecules. The learning path is guided by the Curriculum Model structure and organisation. For example, a student can only start the isotopes part of the virtual lab when they meet the prerequisite of completing the atoms.

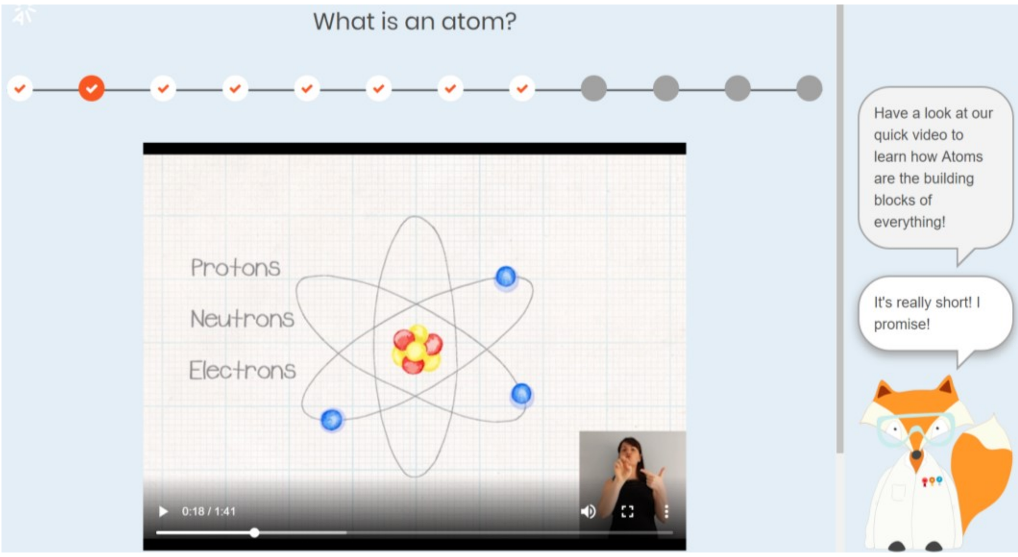

Figure 2: Instructional video of atom with embedded sign language translation to support hearing impaired students.

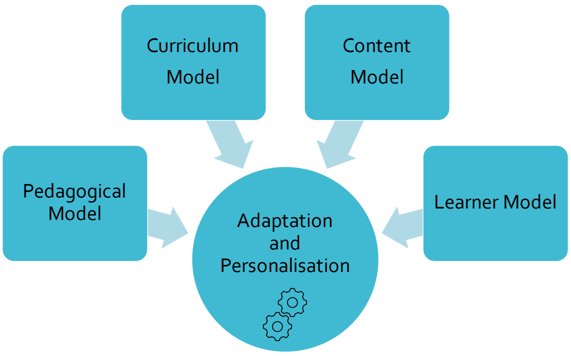

Figure 1: Adaptation and Personalisation input models: Pedagogical Model, Curriculum Model, Content Model and Learner Model.

The Content Model contains various learning materials and contents available in the virtual labs: instructional content with videos, e-assessment, interactivity where students can create and perform their own experiments through inquiry-based learning. The Learner Model is updated during the entire learner journey and includes information about the learner knowledge, level of self-directness, motivation (confidence), and special education needs.

Personalisation in the Atomic Structure virtual lab is implemented at different levels throughout the entire learning journey. The levels of personalisation include:

- learning loop-based personalisation;
- feedback-based personalisation;
- innovative pedagogies-based personalisation (inquiry-based learning, learning in flow, and self - directed learning);
- gamification-based personalisation;
- special education needs-based personalisation (e.g., sign language translation for hearing impaired students as shown in Figure 2).

Student's levels of motivation and self-directness are determined at the beginning of the lab by asking them to answer few questions displayed on the screen. These are used to personalise the difficulty level of questions they receive in the quizzes, what types of atoms, isotopes and molecules they are given to build, as well as what type of feedback they will receive. For example, low and medium motivated students are restricted to atoms, isotopes and molecules which have been deemed suitable to each of those levels, and highly motivated students have access to more complex atoms, isotopes and molecules.

Figure 3 illustrates the process of building an atom of boron with the Atomic Structure virtual lab. The inquiry-based learning phase is offered at the end of each of the three stages in the form of interactive atom, isotope and molecule builders.

Once the students master building the suggested objects, they can freely choose their own objects, and experiment further within the atom, isotope and molecule builders. The Atomic Structure virtual lab also includes gamification elements such as award badges for completing different stages (see Figure 4).

Figure 3: Building an atom of Beryllium.

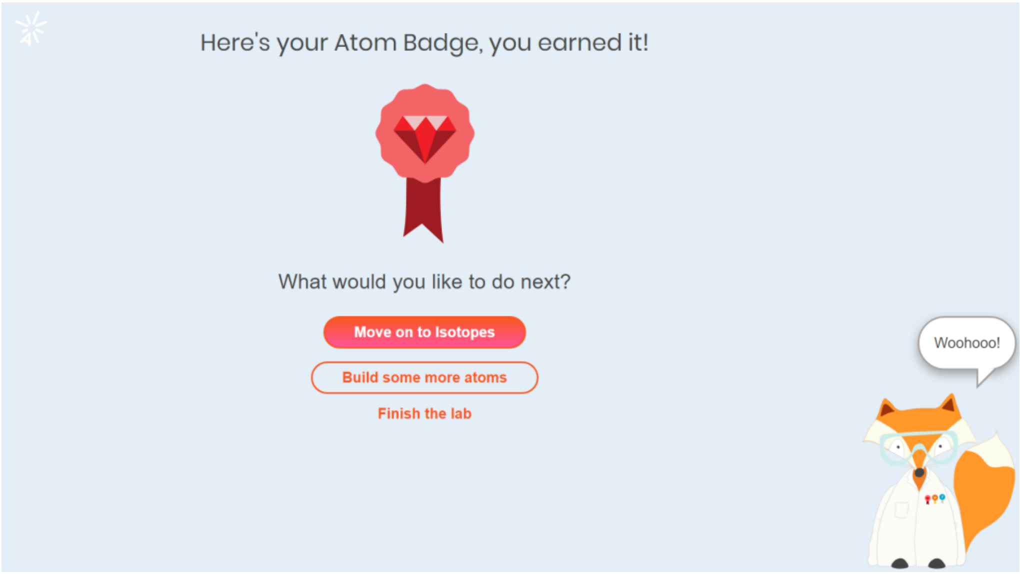

Figure 4: Gamification badge awarded for completing the Atom stage.

4 RESEARCH METHODOLOGY

This section details the research methodology for the case study conducted with the aim to evaluate the Atomic Structure virtual lab in secondary schools.

4.1 Participants

A total of 78 secondary level students from two schools in Ireland have participated into the study. The students were divided in a control group and an experimental group. The wide majority of students (i.e., 69 students) were in the 13-15 age group, 6 students were in the 16-18 age group, and 3 participants did not indicate their age group. The control group had 36 students (23 boys, 11 girls, 2 did not respond) and the experimental group had 42 students (26 boys, 15 girls, 1 did not respond). Students from the control group attended a traditional teacher-led classroom while the students from the experimental group studied by using the Atomic Structure virtual lab on computers in the classroom. The control group was also exposed to the Atomic Structure virtual lab after the evaluation study.

4.2 Evaluation Process

The evaluation of the Atomic Structure virtual lab was done following the multi-dimensional methodology for pedagogical assessment in STEM technology enhanced learning (Montandon et al., 2018). The dimensions assessed were: learning outcome, motivation and learner satisfaction (usability-based). The flow of the evaluation is illustrated in Figure 5, while the assessment procedure is illustrated in Table 2.

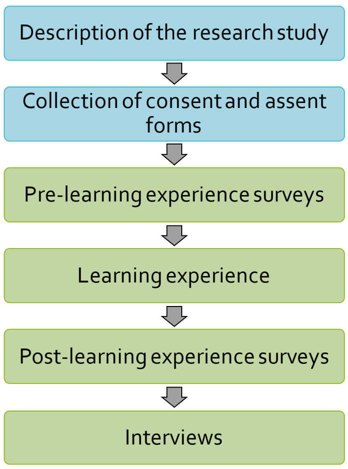

Figure 5: Research study workflow.

A description of the research study was given to participants, and consent and assent forms were collected before the actual study. Pre-learning experience surveys were given before and after the learning experience. The pre-surveys included: demographics questionnaire, knowledge pre-test and learner motivation pre-survey for both the control and experimental group. The learning experience of the experimental group was a personalised learning journey through Atomic Structure virtual lab, while the learning experience of the experimental group was traditional teacher led-class session. Knowledge post-tests and Learner motivation post-survey were given to students from both experimental and control group. Furthermore, the experimental group filled in a usability survey.

The knowledge tests contain both multiple choice and input answer questions. Learner motivation was assessed through dimensions such as interest, self-efficacy, engagement, positive attitude and enjoyment. Interest was assessed through Linkert scale interest question (Moldovan, Ghergulescu, & Muntean, 2017; Ryan & Deci, 2000), self-efficacy (confidence) was assessed following Bandura's guidelines (Bandura, 2006), while engagement, positive attitude and enjoyment was assessed using a 5 point Likert scale (Harmon-Jones, Bastian, & Harmon-Jones, 2016). The usability survey contained questions related to four dimensions (usefulness, ease of use, ease of learning and satisfaction), as well as questions where students were asked to rate tow much they liked different features on the Atomic Structure virtual lab on a 5-point Likert scale, as well as open answer questions to indicate the top three things they liked, top 3 things they didn't like, and if they have any comments or suggestions.

Table 2: Assessment procedure.

Activity	Type	Control Group	Experimental Group
Demographics Survey	Pre-Learning	✓	✓
Knowledge Pre-test	Pre-learning	✓	✓
Learner Motivation Pre-survey	Pre-learning	✓	✓
Atomic Structure Virtual Lab Session	Learning	✓	-
Traditional Teacher Led Session	Learning	-	✓
Learner Motivation Post survey	Post-learning	✓	✓
Learner Usability Survey	Post-learning	✓	-
Knowledge post-test	Post learning	✓	✓
Interviews	Post learning	✓	✓

5 RESULTS ANALYSIS

5.1 Learning Results

An analysis of the pre-test and post-tests knowledge was conducted to investigate the impact of the Atomic Structure virtual lab on students' learning outcome. This analysis excluded the participants that did not answer any question of the pre-test and/or post-test. This approach was treating the participants as absent rather than awarding them a score of 0, which would not be a correct representation of their knowledge level. Participants with true 0 for pre and/or post-test (i.e., answered all questions wrong), were not excluded from the analysis. 11 participants were excluded from the control group and 2 participants were excluded from the experimental group. As such, the pre and post-test scores of 25 participants from the control group and 40 participants from the experimental group were considered for the learning outcomes analysis.

Figure 6 presents the average correct response rates for the control and experimental groups on the pre and post knowledge tests.

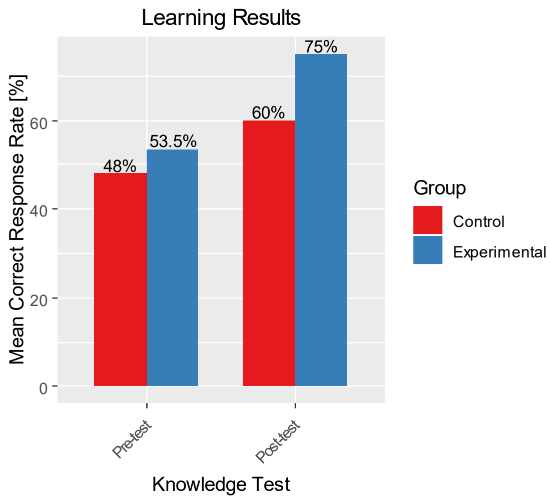

Figure 6: Learning results in terms of mean correct response rates for the two groups.

The experimental group had a mean correct response rate of 53.5% (*SD* = 22.8%) for pre-test and 75% (*SD* = 22.1%) for post-test, which results in a 21.5% increase. The results of a paired t-test for dependant groups showed that the post-test results were statistically significant higher than the pre-test results for the experimental group at $\alpha = 0.05$ significance level ($t(39) = 5.845$, $p < 0.001$).

The control group had a mean correct response rate of 48% (*SD* = 23.1%) for pre-test and 60% (*SD* = 32.1%) for post-test, which results in a 12% increase. The results of a paired t-test showed that the post-test results were statistically significant higher than the pre-test results for the control group at $\alpha = 0.05$ ($t(24) = 2.268$, $p = 0.033$).

The experimental group had 5.5% higher correct response than the control group for pre-test, and 15% higher for post-test. The results of a t-test for independent groups showed that the experimental and control groups had statistically equivalent pre-test score at $\alpha = 0.05$ ($t(51) = 0.938$, $p = 0.353$). However, the post-test results for the experimental group were statistically significant higher than for the control group at $\alpha = 0.05$ ($t(38) = 2.051$, $p = 0.047$).

5.2 Motivation Results

An analysis of the learner motivation and affective state questionnaires filled by the students before and after the session was conducted to investigate the impact of the Atomic Structure virtual lab on students' motivation. This analysis excluded the participants that did not answer all the questions (i.e., 4 participants from the control group and 3 participants from the experimental group). The data from 31 participants from the control group and 39 participants from the experimental group were considered for the learner motivation analysis.

Figure 7 presents the motivation analysis results. The percentage of students answering that they are very or extremely interested in science classes has increased between the pre and post-session questionnaires with 18% for the experimental group and with 9.6% for the control group.

The percentage of students answering that they are very or extremely confident in being able to solve science problems and challenges has increased with 28.2% for the experimental group and with 6.5% for the control group.

The percentage of students answering that they are very or extremely engaged in science lessons has increased with 30.8% for the experimental group and with 9.7% for the control group.

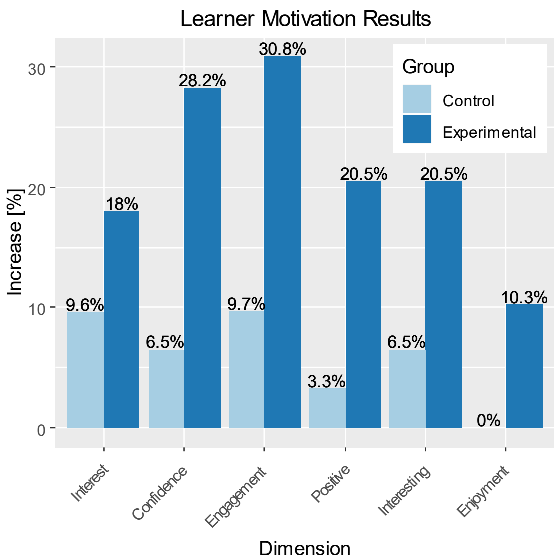

Figure 7: Increase in percentage of learners with high ratings for different motivation dimensions between the post and pre-session questionnaires.

The percentage of students that agreed or strongly agreed that they felt positive during science classes has increased with 20.5% for the experimental group and with 3.3% for the control group.

The percentage of students that agreed or strongly agreed that science classes are interesting has increased with 20.5% for the experimental group and with 6.5% for the control group.

The percentage of students that agreed or strongly agreed that they enjoy science classes has increased with 10.3% for the experimental group but did not change for the control group.

5.2 Usability Results

An analysis of the learner usability questionnaire completed by the experimental group after interacting with the Atomic Structure virtual lab was also conducted. 5 participants were excluded from this analysis as they did not answer all the questions, thus the data from 37 participants from the experimental group were used.

The results analysis showed the following main findings:

- 68.5% of students provided agree or strongly agree ratings and 11.7% of students provided disagree or strongly disagree ratings on usefulness dimension;
- 71.2% of students provided agree or strongly agree ratings and 18% of students provided disagree or strongly disagree ratings on ease of use dimension;
- 81.1% of students provided agree or strongly agree ratings and 6.8% of students provided disagree or strongly disagree ratings on ease of learning dimension;
- 60.4% of students provided agree or strongly agree ratings and 13.5% of students provided disagree or strongly disagree ratings on satisfaction dimension.

Figure 8 also show the percentage of users that indicated that they liked or loved the different features / technology of the virtual lab as follows: 86.5% for videos, 83.8% for quiz and reminder of correct answer after the quiz, 73% for feedback after the quiz, 64.9% for atom builder, isotope builder and receiving badges, and 75.7% for reading facts about atoms and isotopes.

Students also provided subjective feedback. As part of the negative aspects, they mentioned the fact that the atom and isotope builders "took a while" to load and were "sometimes slow", or "it was slow loading the build atom game". One student reported that had to "load the page as it didn't work". Students were using school's computers and internet connection. Another area for improvement suggested by students was to add more "examples or instructions to do the exercises".

As part of the positive aspects, they mentioned "it is easy to use", "it is fun", "it was interesting", "gets to the point", "you can do it yourself". They reported on their perceived learning as well: "I have a better understanding of it now", "my knowledge of the topic has improved", "the videos helped me to learn by hearing", "I liked the quiz as I could see for myself what I had learned", "it helps you understand easier", "I liked how easy it was to understand."

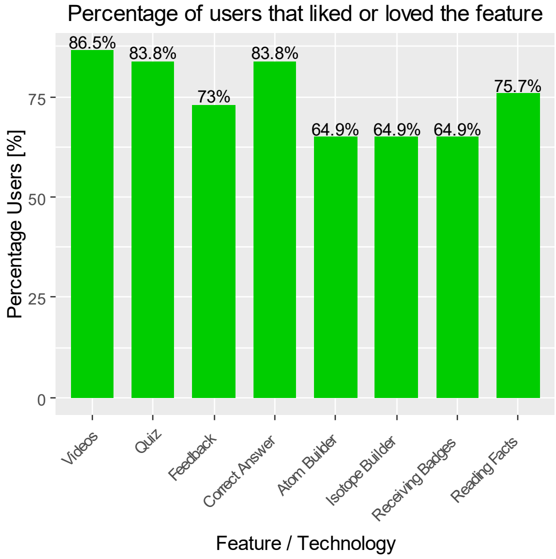

Figure 8: Percentage of learners that liked/loved the different features of the Atomic Structure virtual lab.

6 CONCLUSIONS

Virtual labs have been identified as an effective solution to addressing issues such as the learner's disengagement with STEM subjects, expensive maintenance of physical labs, and availability of experiential learning to online students. Despite the research and development effort, most virtual labs lack personalisation and adaptation, while the evaluation studies often consider only a small number of metrics or questions. This paper has presented results from a comprehensive evaluation of the Atomic Structure interactive personalised virtual lab, with secondary school students. The evaluation applied a multidimensional approach assessing the virtual lab's impact on knowledge achievement, learner motivation, and usability dimensions.

The main conclusion that can be drawn from the learning analysis is that the students using the Atomic Structure virtual had a statistically significant higher knowledge increase than the control group that attended the traditional teacher-led session. The main limitation was the fact that many participants from the control group had to be excluded from the analysis (10 participants did not complete the post-test and 1 participant did not complete both pre-test and post-test). The main observation was that some students ran out of time at the end and did not manage to complete the questionnaire before they left for the next class. Therefore, it is important to better engage with teachers to ensure they give enough time to students to complete the forms within the allocated session timeframe.

The main conclusion that can be drawn from the motivation analysis is that the Atomic Structure virtual lab had a higher impact on increasing learner's motivation as compared to traditional learning. The main conclusion that can be drawn from the usability analysis is that the wide majority of students have provided agree/strongly agree ratings for the different usability dimensions (usefulness, ease of use, ease of learning and satisfaction), and liked/ loved the features/ technology for the virtual lab.

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