Augmented Immersive Reality (AIR) for Improved Learning Performance: A Quantitative Evaluation

Ling Cen, Dymitr Ruta, Lamees Mahmoud Mohd Said Al Qassem, and Jason Ng

***Abstract*—Technology-enhanced learning has attracted increasing attention of educational community focused on improvement of traditional classroom learning. Augmented immersive reality (AIR) technologies enhance users' perception of reality by augmenting it with computer-generated components such as audio, video, 2/3-D graphics, GPS data, etc. The AIR introduces new dimensions of learning experience that ensure better attention, focus and entertainment, thereby boosting students' motivation and attainment. This work presents an award winning AIR-based educational mobile system, code-named AIR-EDUTECH, that was developed to help high school students learn chemistry. The AIR-EDUTECH introduced new AIR features to help students better understand and learn basic concepts of molecular chemistry. It offers immersive 3D visualization and visual interaction with the examined structures that provides a broader and more retentive knowledge and improves intuition around forming basic chemical reactions. The system was introduced and tested in a field study with 45 students in the 11^{th} grade chemistry class, and its impact was evaluated by the formal assessment quiz along with the feedback from survey conducted after the trial. Collected data have been subjected to an in-depth multi-modal quantitative analysis that revealed that AIR-EDUTECH stimulated significant improvements in understanding and retention of the taught content as well as turned learning chemistry into a fun, interesting and interactive experience. It also uncovered a hidden structure of taught knowledge dependencies and highlighted the role that AIR technology could play in reinforcing the retention of critical knowledge that may otherwise widen student knowledge gaps.**

***Index Terms*—Mobile learning, Augmented Reality (AR), Augmented Immersive Reality (AIR), AIR-EDUTECH, education data mining**

I. Introduction

WITH the rapid development of emerging technologies such as augmented reality (AR), virtual reality (VR), ubiquitous learning (u-learning), and mobile learning (m-learning), technology-enhanced learning (TEL) has attracted increasing attention of education community in an attempt to enrich traditional learning experience with an interactive and multi-modal learning environment [1]-[6]. By integrating and adopting new technologies to education curricula, TEL enhanced the learning experience in many aspects, e.g. customizing learning material and processes, aiding inspirational and innovative teaching, encouraging student engagement, helping knowledge retention, training memory, increasing satisfaction and making learning more fun and interesting.

Augmented reality offers a live, direct or indirect view of a physical, real-world environment whose elements are augmented by computer-generated components such as audio, video, 2/3-D graphics, GPS data, etc. Unlike virtual reality that simulates a virtual environment to replace the real one and completely immerses users inside the synthetic environment [7], AR supplements the surrounding real world by augmenting it with virtual, computer-generated overlay added to the physical environment through a auxiliary sensory mechanism [8] and allowing users to see the real world with virtual objects superimposed on the real world [7]. AR applications generate and enable a common space where virtual and real objects coexist in a seamless way, and enhance users' perception of reality by providing them with an interactive environment and digitally manipulated virtual/real information [7], [9]. Augmented immersive reality (AIR) lies between the AR and the physical environment and offers more enhanced experience with the examined reality through the artificial components added or blended into the scene to improve its perception [10].

It has been shown that AR technologies can help to increase learning motivation of students and enhance the quality of learning experience [2], [11]-[26]. Summarizing the findings from the reported research, the major benefits of using AR in education come in the following forms [2]:

- improved learning performance and retention,
- promoting learning motivation and interest,
- inspiring student positive attitudes,
- improving perceived enjoyment,
- increasing student engagement,
- encouraging more exploration,
- providing facilitated interaction,
- decreasing education cost,
- enhancing learning experience,
- providing augmented information,
- creating student-centered environment,
- bringing more collaboration in the learning process,
- increasing capacity of innovation,
- increasing awareness and authenticity of learning.

This work carries out an investigation of the use of AIR technologies in specific education scenarios of taught molecular chemistry and identification of its impact on learning performance. The major contributions are concluded as follows:

1) Presentation of a new AIR-EDUTECH educational mobile system, which introduces an interactive AIR environment to help high school students comprehend

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molecular structures and better understand their interactions in the context of chemical reactions formation.

2) A feedback from a field study carried out with the support of AIR-EDUTECH on 45 11^{th}-grade high school students of the chemistry course, split into 2 groups, one supported by the AIR-EDUTECH, and the other following traditional chemistry course with boards and pens. The results and the quantitative analysis of the quiz and a survey conducted after both groups completed the trial are reported below.
3) An in-depth quantitative insight on the impact of the AIR-EDUTECH on the learning performance in the molecular chemistry context along with the identification of the key drivers explaining the critical elements of this impact. Unlike many other predominantly qualitative research carried out in this domain [2], our results emerge from a comprehensive quantitative analysis carried out on the real data collected in the field study and feature:
   a) Distribution analysis of quiz scores with a clear improvement of learning outcomes for the AIR-EDUTECH supported group.
   b) The statistical significance test verifying the reliability of the posed hypothesis of AIR-EDUTECH stimulated improved learning.
   c) Association analysis with the indications that the AIR educational system helps students to gain better understanding of the presented material.
   d) The analysis of the survey responses revealing that the most of the students were satisfied with the learning experience aided by the AIR-EDUTECH and preferred it over the traditional methods.
4) Supplementary quantitative analysis revealing several additional insights like the capability of the AIR-EDUTECH to reveal the hidden structure of the taught content and thereby reinforcing the retention of its critical components to eliminate deep knowledge gaps.

The positive results achieved in this study provide a great prospect for replication of the AIR technology benefits across other education curricula and offer a founding reference to help to stimulate similar efforts whenever a successful and retentive knowledge transfer is involved.

The remainder of the paper is organized as follows. The AR/AIR based systems developed in the literature are briefly reviewed in Section II. The AIR-EDUTECH system is described in detail in section III. The scenario of the field study is presented in IV. In Section V, the comprehensive quantitative analysis based on the collected data is carried out and follows with the concluding remarks presented in Section VI.

II. Related System Review

AR technologies have been applied in education across multiple fields, e.g science and engineering, humanities and arts, social sciences, business and law, targeted to groups of all ages from primary and secondary education to bachelor's or equivalent level, in both formal and informal setting, [2], [3], and compared to traditional teaching, they better support interactive applications running in real-time [27]. With the advancement of AR/AIR technologies and the increasing popularity of mobile devices and wireless technologies, great opportunities for more creative applications in education are being explored, e.g. to better explain the content enriched with augmented information, or to teach through highly immersive and interactive AR educational games or lab experiments [2].

The Magic Book [28] is an early attempt to explore how to smoothly transport users between reality and virtuality, which despite the ordinary appearance, has 3D virtual models appearing out of its real pages to provide animated, dynamic virtual content that brings more fun to readers than traditional 3D pop-up books. The augmented book of AR-Dehaes provides 3D virtual models to help students perform visualization tasks in a short remedial course [7]. It is shown in the validation study conducted with 24 mechanical engineering freshmen at La Laguna University (Spain) that the AR-Dehaes is able to improve the spatial abilities of students [7]. The augmented reality solar system (AR-SS) is designed using the AR technology to help primary school students understand the basic astronomy by providing the live videos of solar system and audio clips of planet animations [29]. The GeoAR is an interactive book designed for teaching and learning geometry shapes, which displays markers in pages of the book and provides explanation on geometric shapes [30]. The AR-based animations, audio and 3D objects used in the book make the GeoAR attractive and stimulative to children [30]. The Augmented Chemical Reactions (ACRs) help students learn spatial structures of chemical molecules. The ACRs visualize the structure of molecules and allow direct interaction with virtual molecules [31]. The manipulable 3D user interface of the ACRs allows users to change the orientation of chemical molecules and generate reactions among different molecules, which provides the impression of being in a real lab and seeing the augmented objects as parts of the real environment [31]. Another AR system for teaching chemistry at high school level is reported in [27]. It supports multiple groups of students interacting with elements and compound structures in a collaborative environment, bringing more enjoyment during learning and achieving better understanding on presented material. An AR based remote lab is presented in [32]. Unlike virtual remote labs that lack reality and complete visualization capabilities, it allows students to carry out engineering experiments represented by both real and virtual elements, components and equipment, and thus helps to overcome the drawbacks of hands-on labs, e.g. availability, cost, health and safety risks, lack of instructors and infrastructure, etc. It also gives students more freedom to choose whatever and whichever way they want to carry out lab activities without the risks of adverse effects.

III. System Description: AIR-EDUTECH

Chemistry is one of the fundamental sciences in high school education. Both teaching and learning chemistry are challenging tasks. It encompasses many abstract concepts and 'invisible' elements, e.g. molecules, that cannot be observed with our naked eyes in real life. Since chemistry is heavily intertwined with mathematics and physics, it is often perceived as a difficult subject and unless appropriately supported, leaves students struggling to comprehensively grasp complex concepts in chemistry, which in turn may dent their interest, motivation and focus. AIR technologies are capable of enhancing the sense of reality by superimposing virtual components, e.g. video, audio, 3D objects, etc. in real environment. Our proposition is to utilize these benefits in a specific education context of secondary school chemistry course with the support of an AIR based mobile education system, code-named as AIR-EDUTECH, developed at (EBTIC) Khalifa University [33]. It received the third place award in the 2016 IEEE Student Day Competition in the UAE and scored the second place in the 2016 UAE Mobile Application Contest (MAC'2016). AIR-EDUTECH provides students with an interactive AIR learning environment, within which they can visualize and manipulate 3D molecular structures along chemical reactions as a part of their 11^{th}-grade chemistry curriculum. The tool has been developed specifically to boost students' grasp and understanding of abstract chemical concepts and complex molecular structures and more generally to attract their interest and enhance overall learning experience, compared to traditional learning methods in chemistry.

A. Overview of System

The proposed AIR-EDUTECH system consists of a set of components centered around the mobile phone to exploit its sensory and data processing capabilities. The AIR technology is enabled through the interaction of a set of predesigned cards with chemical substances or element structures printed on and the AR smart phone application that visually senses the real world with the camera and live augmenting the perceived view with the VR objects. The mobile application has been developed using Unity engine [34] and Vuforia AR SDK [35] and can run across multiple platforms (i.e. Android, IOS, Windows). The application is capable of detecting the card presence, recognizing their content, and visualizing corresponding chemical reaction with the enhanced AIR elements on the mobile phone screen or other display units. Users can interact with the system by using these cards to choose what educational contents they are interested to learn about. To attract students' attention and enrich their learning experience the material is augmented with interactive graphics, animations and other edutainment features.

The system architecture is shown in Fig. 1. It consists of Unity application that runs on the mobile phone and in a summary works by reconciling the visual input from the camera with the stored database of targets and depending on the outcome triggers various interactive actions. It reuses the device's sensory, storage and projection components (camera, display screen and image target database) and combines them with Vuforia components to manage the execution and logic of virtual objects augmentation. On the start of the application, the mobile's camera is linked to the virtual camera in the scene and the Vuforia tracker. The virtual camera links the application with the Vuforia database to detect and recognize the 2D objects. The tracker uses visual pattern recognition technology and pre-stored models on the local database to

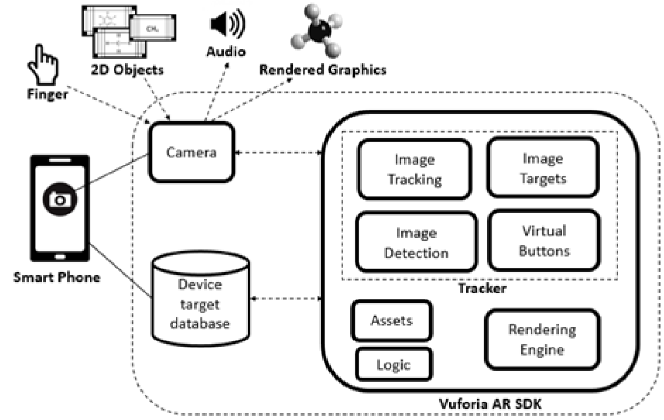

Fig. 1. AIR-EDUTECH System architecture.

Fig. 2. Examples of two different facial textures.

detect the targets printed on the cards and provides the state of the object required as input for the rendering engine and logic processor. Based on the scripted and customized logic the system then renders the output view on the display unit. The output view contains a combination of the real camera-captured reality with the overlaid VR 2D/3D objects, and the audio stream that provides verbal description of the chemical compound or reaction involved in an interaction.

B. System's Features

The system is designed to visualize chemical structures and their reaction using sphere-and-sticks model of molecules immersed within rich multimedia content including audio, video, and 2D/3D animation. The 3D models are downloaded from 3D Warehouse (https://3dwarehouse.sketchup.com), Assets store (https://www.assetstore.unity3d.com/), or created with SketchUp - a popular 3D modeling tool and animated using the Unity's animation options by repeatedly changing time positions and altering the object accordingly. Multiple clips or basic animations are managed by an animator controller to create complicated animation based on the concept of finite state machines (FSMs). Animation illusion is also achieved by alternating textures, e.g. dragging smiling texture over the face of the character in a certain state to make it looks like smiling, as shown in Fig. 2. The character is an object used in the scenes in order to make the scenes more attractive to students, which is able to show different emotions, make movements, and give extra scientific information about chemical compounds and reactions.

To allow interaction between users and the system, a set of cards are provided, each of which represents a chemical substance or an element. When the system detects one or more cards put towards each other in the camera view, the contents of the cards, i.e. their corresponding chemical reaction or molecule structures, will be recognized and corresponding actions related to the cards will be taken by the system according to the scripted logic.

Two topics selected from the syllabus of the 11^{th}-grade UAE high school are covered in the system, which are:

1) General topics in chemistry showing the reactions among any combination of four common elements ($O_2, H_2, Cl_2,$ and Na);
2) Organic chemistry, emphasizing the structure and the usage of carbon compounds.

Two scenes corresponding to each topic are created and in both cases the focus is on assisting the process of learning through interactive visualization of chemical reactions using sphere-and-sticks molecule models.

In the general chemistry scene, the reactions among 4 commonly used chemical elements, i.e. O_2, H_2, Cl_2 and Na, are presented, including the reactions of any combinations of the original elements and their products. For example, H_2O is the product of the reaction between O_2 and H_2:

$$2H_2 + O_2 = 2H_2O, \quad (1)$$

which reacts with Cl_2 to produce HCl and O_2.

To show a chemical reaction among two or more substances or elements, one can approach the corresponding cards close enough to each other in the camera view. The reaction will be triggered and displayed on the screen of the device as long as enough cards are added to construct a balanced chemical equation. The reactions are implemented based on the concept of collision. A collision is detected by using Box Colliders and Rigid Body. In the collision of two elements (or image targets), the box collider of one element is served as a trigger, and that of another is attached with a Rigid body. The dynamic collider is fully simulated by the physics engine capable of detecting and reacting to collisions and physical forces applied [31]. The collisions are triggered by the card representing a lab container. To explain this, we use again the example in (1). To start the reaction, the card representing a beaker is used first. The element of H_2 is then added into the beaker by letting the H_2 card touch the beaker card, following that, O_2 is added in the same way. Since the reaction requires 2 H_2, the user will be asked to add one more H_2 by pressing a button. Once completed, the reaction is displayed on the screen. Exiting a reaction and emptying the beaker can be realized by either pressing the Exit Reaction button or taking the reacting substance cards away from the beaker card. This process helps students learn chemical reactions in a more intuitive and retentive way, compared to the traditional methods. Besides the reactions among elements, the AIR-EDUTECH system provides also related useful chemistry knowledge and facts like: "NaCl is the salt that is commonly used in cooking".

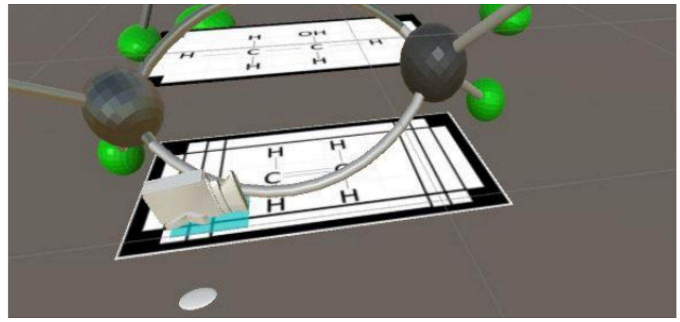

Fig. 3. Virtual button below a camera model.

In the organic chemistry scene, the sphere-and-stick model is shown on the screen when a card with a corresponding molecule is detected. Instead of using collision to trigger chemical reactions as in the general chemistry scene, virtual buttons located on the image targets are used here as triggers. Touching different parts of a card triggers different functions, e.g. showing 3D models, linking online videos that are related to the presented material, etc. Fig. 3 shows an implementation of a virtual button with a camera model added on top of it to mark its position as virtual buttons are naturally invisible.

Another useful feature is spatial interaction between users and the device controlled by their mutual spatial distance. Different distances correspond to a different 3D model or a function upon the corresponding element or compound. As shown in Fig. 4, bringing the card closer to the device displays the usage of the element (a), while increasing the distance triggers the sphere-and-stick model shown on the screen (b).

IV. Field Study Scenario

To evaluate the developed AIR-EDUTECH system and assess the impact of the AIR technology it introduces in the context of learning chemistry, a field trial has been implemented and conducted in a traditional classroom environment throughout a 11^{th}-grade chemistry course in a selected public high school in Abu Dhabi, approved by the Abu Dhabi Education Council (ADEC).

The trial was conducted at the end of the last term when the final grades were already available. A total sample of 45 female students were divided for the purpose of the analysis into two similar but differently labelled groups: the *non-app group* with 20 students, and the *app group* with 25 students. The end-of-term timing of the trial helped to compose each group with similar roughly uniformly distributed academic performance of students. Specifically each group included around 20% of high-performing students whose module final scores were higher than 90%, 30% of low-performing students with scores below 70%, and 50% of middle-class students scoring in-between. The students from each performance rank were randomly assigned into 2 groups, thereby ensuring fair performance agnostic comparison at the group level, yet availing at the same time to measure the magnitude of the impact of the general academic performance on the level of benefit or detriment stimulated by AIR-EDUTECH.

All students were taught exactly the same chemistry material by the same teacher in the same class duration, i.e. 45 minutes.

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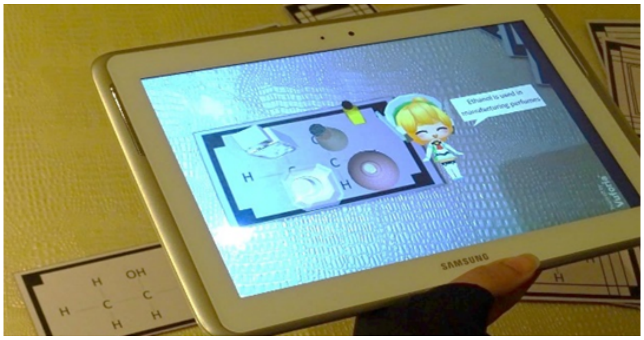

(a) The device is closer to the card, the usage of the element is displayed.

(b) The distance is increased, the sphere-and-stick model is displayed.

Fig. 4. Spatial distance-controlled interaction between the card and the device.

Both lessons were given on the same day directly after each other. The lesson for non-app group was first provided followed by the app lesson. For both groups the teacher was asked to deliver the material in the traditional way she usually did, e.g. illustrating the structures of compounds/elements using figures in the book, writing in a white board, conducting group exercises with students etc., with the only exception that the app group students were additionally supported by the AIR-EDUTECH application and the activities it stimulated throughout the session. After the application was briefly demonstrated by the teacher at the beginning of the class, the app-group students were organized into small sub-groups to better understand and explore the system and with the support of the application to work together on the classroom material. The students were only allowed to use the application when the teacher asked a question or gave an exercise (e.g. work sheet) during the class, e.g. looking for the usage of an organic compound. Each sub-group was required to complete the task by using the application along with the class notes if needed. It is important to note that the non-app group was also divided into sub-groups and had the same group exercises, although they were only allowed to use their class notes to answer the questions and do exercises. In summary while non-app group of students were working interactively in small groups on the tasks being sort of restricted to themselves, their imagination and notes, the app-group of students were also working together interactively in small groups but their work was supported by virtual chemistry lab in which they were trying, experimenting and engaging in the virtual chemical reactions without any hazards of the actual physical reactions in case of mistakes. They shared and discussed observed experiences and were seen to mutually excite and encourage themselves to try different reactions all in a pleasant and fun atmosphere.

Immediately after each teaching session, the students were asked to complete a short assessment quiz, which included a variety of multiple-choice questions on organic chemistry and the chemical reactions taught during the trial. All students were required to complete the quiz in 10 minutes. The quiz was validated by the teacher to ensure that all main topics were covered and the questions adequately assessed their understanding and retention of the taught material. After the quiz, the AIR-EDUTECH system was given to all students in both groups for their exploration of all features of the application. A survey was handed to the students to gather their feedback indicating their impression of the application and their thought of using the AIR technology in education and in classrooms.

V. Field Study Evaluation

During the experiment, it was observed that the students taught with the AIR-EDUTECH exhibited higher enthusiasm for exploring and interacting with the taught content compared to those using the traditional method. They were impressed by the 3D models visualization of the chemical elements as well as the enriched audio content. Specifically, they loved the feature of the spatial interaction whereby the molecules automatically transformed into their real-world form when the device was brought into close proximity with the cards. However, they did not like adding more molecules to balance an equation before proceeding to the reaction result, although this feature was intentionally added to ensure reinforced learning of the students. They commented that it is much easier to show the result directly since they can already see the balancing of the equation in the display. The results of the quiz and the survey were compiled and organized to produce a thorough quantitative analysis of the results as elaborated below.

A. Score Distribution

Fig. 5 shows the grades scatter plot color-coded for both groups, i.e. the app group who used the AIR-EDUTECH in their learning (red) and the non-app group who studied in a traditional way without using the AIR-EDUTECH (blue). Each point represents the score of a student and the dotted lines mark the average scores of the 2 groups along the student group size it was computed. As illustrated in Fig. 6, more red points (scores of the app group) are located in the upper part leaving more blue points (scores of non-app group) below, which indicates that the students exposed to AIR-EDUTECH tend to score higher than the traditionally taught students. This is also clearly reflected by the average score of 7.36 in the app group, which is 53% higher than the average score of just 4.8 in the non-app group.

Fig. 6 compares the score distribution of the 2 groups, in which the horizontal axis denotes the marks, and the vertical axis represents the number of students. The lowest score

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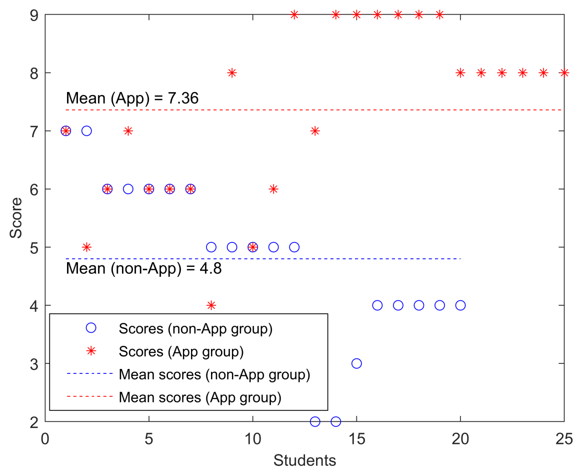

Fig. 5. Grades of the quiz achieved by the two groups.

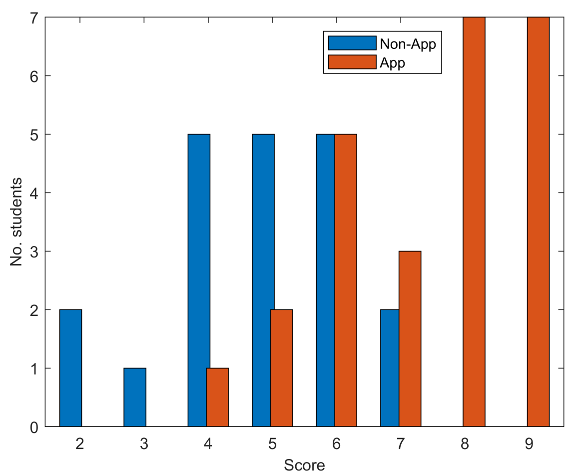

Fig. 6. Distribution of the quiz grades.

achieved by the students who did not use the AIR-EDUTECH is only 2, while the users of the app scored at least 4. 8 students among 20 in the non-app group scored 4 or lower, while only 1 among 25 in the app group scored 4. Performance improvement is observed among the top students as well. Seven students in the app group achieved full marks, while no students in the non-app group got the maximum of 9 points. The highest score in the non-app group was 7 achieved by only 2 students. These performance results, also summarized in Table I, clearly indicate that the AIR-EDUTECH has the capability to improve learning performance of both high and low performing students.

Fig. 7 illustrates the numbers of the students who correctly answered specific questions. The three bars for each question, individually show the numbers of the students of the non-app and app groups, as well as their total and are accompanied by their corresponding percentage for clarity. In this figure, the questions are sorted in an ascending order of the total number of students who correctly answered specific questions, hence the sorted question *id* could be associated with the question

TABLE I
COMPARISON OF QUIZ PERFORMANCE BETWEEN THE 2 GROUPS

Group	No. students	Min. score (No. students)	Max. score (No. students)
Non-App	20	2 (2)	7 (2)
App	25	4 (1)	9 (7)

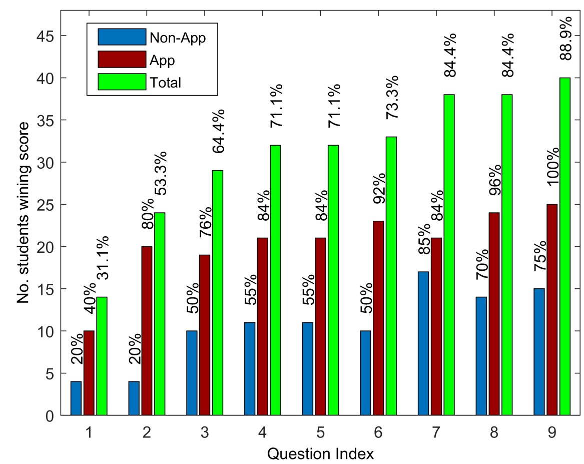

Fig. 7. Sort scores distribution among questions.

difficulty level. Except for the 7^{th} question that was correctly answered by about 85% of students in each group, there were overall significantly larger absolute and relative numbers of students in the app group who answered correctly compared to the non-app group. Moreover, it can be seen from Fig. 7 that except for the hardest first question, the students in the app group achieved stable performance with a percentage range of 76% – 100% across the question difficulties. On the other hand, the students' performance in the non-app group is quite unstable and ranges from very low 20% for difficult questions to 85% for easier questions. For the first 2 questions, seen from the figure to be the most difficult since they were answered wrongly by most (80%) of students in the non-app group, the app-exposed students scored much better. The contrasting performance is particularly visible for the 2^{nd} question that was answered correctly by 80% of app-group students compared to only 20% of the non-app students. In addition, it is found that some students in the non-app group did not complete all questions, specifically, 3 students answered 8 questions and 1 students answered only 5 questions, while all the students of the app group gave the answers to all the questions on their answer sheets. The above results indicate that the AIR-EDUTECH can help students in 2 aspects:

1) improves learning performance of students irrespective of their proficiency level;
2) helps especially weaker students understand difficult material better.

Let us further discover the impact of the system on learning outcome along the perceived difficulty of the taught content.

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The performance improvement achieved by using the AIR-EDUTECH is measured using the difference between the average scores of the app and non-app groups, given as

$$imp_q = \frac{\sum_{s=1}^{S_A} grade_{qs}}{S_A} - \frac{\sum_{s=1}^{S_N} grade_{qs}}{S_N}, q \in Q, \quad (2)$$

where imp_q is the improvement achieved in the q^{th} question by using the AIR-EDUTECH system, Q is the set of question indices, i.e. $[1, 2, ..., 9]$ in this study, $grade_{qs}$ is the score achieved by the s_{th} student in the q^{th} question and can be either 1 or 0 in our settings, S_N and S_A are the total numbers of students in the non-app and app groups, respectively, and we have $S_N = 20$ and $S_A = 25$ in this study. Let $diff_{q-A}$ and $diff_{q-N}$ denote the difficulty levels of q^{th} question that are measured based on the average scores of the app and non-app group, respectively, given as:

$$\begin{aligned} diff_{q-A} &= 1 - \frac{\sum_{s=1}^{S_A} grade_{qs}}{S_A}, \\ diff_{q-N} &= 1 - \frac{\sum_{s=1}^{S_N} grade_{qs}}{S_N}, \\ q &\in Q. \end{aligned} \quad (3)$$

By substituting (3) in (2), we have:

$$\begin{aligned} imp_q &= (1 - diff_{q-A}) - (1 - diff_{q-N}) \\ &= diff_{q-N} - diff_{q-A}. \end{aligned} \quad (4)$$

This indicates that the improvement achieved by using the application corresponds to the reduction in difficulty levels of the questions. Indeed, part objective of the application is to turn seemingly difficult tasks easy.

The improvement is then sorted according to the difficulty level of questions. We preferred to stick to the interpretation of the question difficulty as seen prior to the AIR-EDUTECH introduction. Otherwise the meaning of objective difficulty becomes contaminated since what is difficult prior the app use could become easy when taught with the application. The improvement is, therefore, sorted according to $diff_{q-N}$. As illustrated in Fig. 8, each point corresponds to one question with the x, y coordinates corresponding to question difficulty and performance improvement, respectively, and is additionally labeled by the actual index of the question in the quiz. The red dotted line shows the linear trend fitted to the points using simple linear regression and it appears to be rising at a rate of around 0.5 points per unit of question difficulty. This indicates that the improvement tends to grow larger when the questions are getting more difficult.

B. Mistake Pattern Analysis

All of the questions in the quiz are multiple choice questions. For each question, there are 3 choices for answer with only 1 correct and 2 incorrect answers. In order to establish the impact of the system on the students performance in more detail, we have explored different patterns of error distribution between the two groups. We define the average imbalance

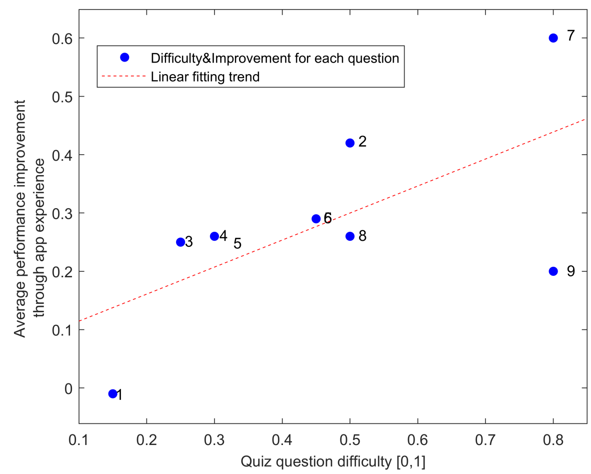

Fig. 8. The impact of app experience on quiz question performance gain.

between error answers as the normalized difference of the times that the 2 error choices were chosen, given as

$$imbal_q = \frac{|n_{qa1} - n_{qa2}|}{n_{qa1} + n_{qa2}}, q \in Q, \quad (5)$$

where n_{qa1} and n_{qa2} are the number of students who chose the wrong choices of a_1 and a_2 in the q^{th} question. In one of the extreme cases, the average imbalance of a question is 0 if both of its 2 errors are chosen by equal numbers of students, where independent errors may reflect simply ignorance. On the other end, the imbalance is 1 if the students who wrongly answered the question all selected the same error choice, which may reflect correlated misconception about the asked content. The imbalance is calculated individually for the two groups, which is depicted in Fig. 9 and distinguished by color shade. It can be seen from the figure that in the app group the average error imbalance for most questions is higher than 0.5 and for 5 questions it reaches the maximum value of 1. For the non-app group, however, the imbalance of most questions is below 0.5, and only for 1 question reaches the maximum value. This indicates that the students who used the application tend to choose the same error answers in most questions, while those who did not use the application are more likely to chose both error answers with a random probability. This phenomena could be explained by the following two effects:

1) Students in the non-app group have poorer understanding of the taught knowledge and are more likely to make randomly distributed errors when asked to answer the related questions. Students in the app group understand the content better hence they make far fewer mistakes (1-2) that could incidentally correlate.
2) The wrong answers are not equally wrong. Since the app group students understand the content better they may have chosen answers that, although erroneous, are closer to the correct answers, while non-app students are less capable of distinguishing differences among (especially wrong) answers, hence make random mistakes.

A closer inspection of the errors made within the app group confirms both of the above explanations although more influ-

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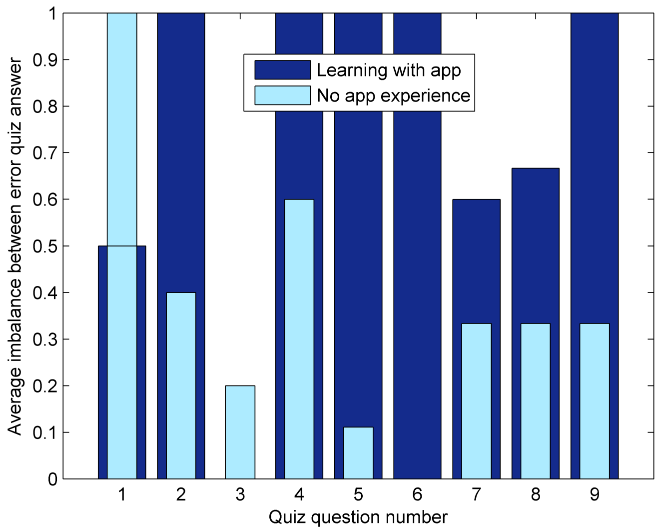


Fig. 9. The impact of app experience on quiz question error imbalance.

ential seems to be the first effect since for the questions with maximum error imbalance there are typically only 2 students who made the same mistake by accident.

C. Statistical Significance Test

The above-shown analysis carried out on the real data extracted from the field trial confirms that the AIR-EDUTECH does improve learning performance and understanding of the taught content compared to traditional learning. Since the data size is small, Fisher's exact test [36] was carried out to determine if there are non-random associations between learning improvement and the use of the AIR-EDUTECH.

In the statistical significance test, the null hypothesis (denoted as H_0) and the alternative hypothesis (denoted as H_a) are defined as:

- H_0: Students' utility of the AIR-EDUTECH app has no association or impact on the performance improvement.
- H_a: Students' utility of AIR-EDUTECH app has non-random impact on the attained performance improvement, specifically usage of the app improves the performance scores compared to learning without the app.

To construct a contingency table, let us take the 1.1 times of the average score of the non-app group that is 4.8 as a benchmark, i.e. 5.28. The students scoring higher than the benchmark are considered to be improved and those with equal or lower scores are not improved. As shown in Table II, there are 2 groups, i.e. non-app and app groups, and 2 classes, i.e. improved performance and non-improved performance. Among the 25 students who used the AIR-EDUTECH, 88% scored higher than the benchmark, while only 35% of the 20 students in the non-app group achieved higher scores.

The exact hypergeometric probability of obtaining any such set of values given in Table II, assuming the given marginal totals, on the null hypothesis, can be calculated as

$$p = \frac{(7+13)!(22+3)!(7+22)!(13+3)!}{(7+13+22+3)!7!13!22!3!}, \quad (6)$$

TABLE II
IMPROVEMENT OF LEARNING PERFORMANCE OF THE 2 GROUPS

	Improvement	Non-improvement	Total
Non-App	7	13	20
App	22	3	25
Total	29	16	45

where the symbol '!' denotes the factorial operator.

To calculate the significance of the observed data, i.e. the p-value that is the total probability of obtaining a result equal to or more extreme than what was actually observed if the null hypothesis is true , the hypergeometric probabilities for all possible cases need to be calculated and summed together. As suggested by Fisher [36], we only need to consider the cases where the marginal totals are fixed to be the same as in the observed table, and have in total 21 cases based on the smallest marginal total, i.e. 7 + 13 = 20. The two-tailed $p-$value in the Fisher's exact test then gives the value of:

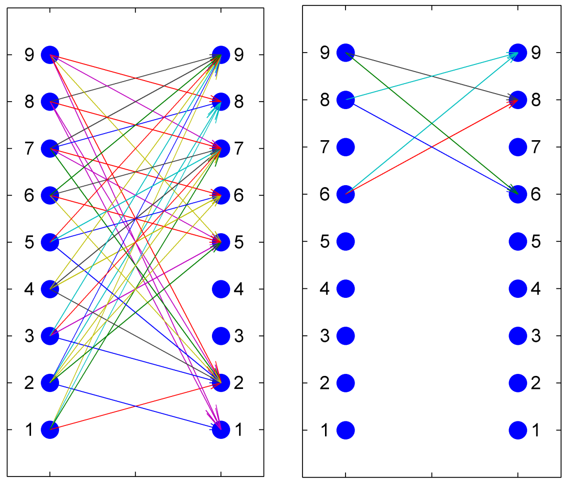
$$p - \text{value}_{2-tailed} = 0.0004. \quad (7)$$

It is much smaller than 0.05 that is usually used as a standard significance level corresponding to the 95% confidence level. The test suggests that the observed data are inconsistent with the null hypothesis, which is equivalent with the statement that the association between the app usage or non usage (rows) and the performance improvement (columns) is extremely statistically significant. Based on the test and on the observed direction of the correlation, it can thus be reliably concluded that the students who use the application for learning selected chunks of chemistry course, tend to achieve much better scores than those without using this application.

D. Association Rules Mining

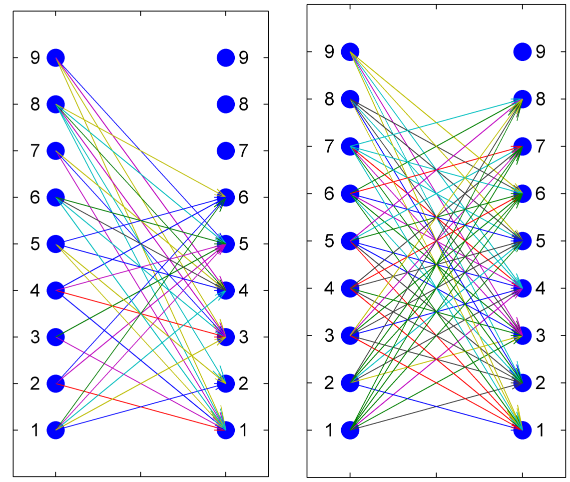
To complement our analysis and reveal further insights related to the associations among different questions and answers, we approach the same problem using different analytical apparatus of association rules mining. The intention is to automatically discover the significant associations among the quiz questions, students answers to them and the impact of the AIR-EDUTECH usage inferred through student grouping. In general, given a set of transactions, association analysis intends to extract rules for predicting the occurrence of an item based on the occurrences of other items in the transaction, which is useful to discover interesting relationships hidden in large data sets [37]. The uncovered relationships can be represented by association rules, e.g. $A \rightarrow B$ indicating strong dependence of the occurrence of B on occurrence of A. Association rules mining has been heavily utilized in data analysis across many domains, industries and application areas, e.g. biomedical, experimental physics, e-commerce, etc.

In our context of exploring the associations between correct and incorrect answers provided by the students during the assessment quiz, the association rules mining has been carried out by utilizing the Apriori algorithm [38]. The minimum of support that is the probability of both A and B occurring at the



(a) No-app group (b) App group

Fig. 10. Associations among wrongly answered questions in both groups.



(a) No-app group (b) App group

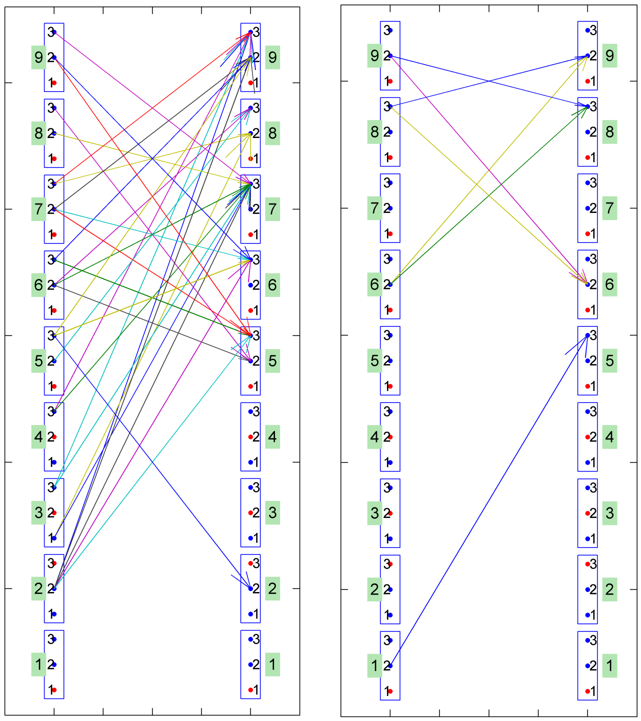
Fig. 11. Associations among correctly answered questions in both groups.

same time is set to $p_{min}(A, B) = 0.1$, while the minimum of confidence - that is the conditional probability of B occurring given A is set to $p_{min}(B|A) = 0.75$. Fig. 10 illustrates the associations among the 9 questions based on the frequency at which they were answered wrongly by either the students who did not use the application (a) or those who used the application in their learning (b). In each plot, there are 2 columns of points, each of which represents one question with the corresponding index. The arrows linking the question points from the left to those in the right illustrate the associations among the corresponding questions. The links basically embody the conditional probabilities of making errors, which means that making an error for the question on the left side of the link increases the probability of also making an error for the question pointed to on the right side of the link. The associations reveal also the knowledge correlation and the relevance of the questions in the quiz. As illustrated in Fig. 10, the association patterns of the two groups are significantly different with much more links shown in the non-app group than in the app group. All questions on the left side are linked to the 2^{nd}, 7^{th} and 9^{th} questions on the right, which indicates that these three questions are probably the most difficult, highly relevant and composite questions that are dependent on the knowledge required to correctly answer all other questions. Also multiple links originating from a questions node, like in the case of question 2, indicate that the knowledge required to solve this question is most likely fundamental and enables to also solve many other questions. On the other hand, the error associations in the app group are quite simple and infrequent at these levels of support and confidence featuring only 6 links in total. Most of the strong associations observed in the non-app group do not exist in the app group, which indicates that the students exposed to learning with the AIR-EDUTECH better understood taught content to the extent that the deep-rooted correlated knowledge gaps are eliminated and there is little or no dependence between errors made for different questions.

Similarly, Fig. 11 depicts the associations among the questions according to the frequency of their corresponding correct answers. Given the previous evidence it is perhaps expected to observe that the links in the app group are plentiful and much more widespread compared to the non-app group. As an example shown in the figure, correctly answered the $1^{st} - 3^{rd}$ and $5^{th} - 7^{th}$ questions , significantly increase the chance of correctly answering question 8, while no such association link exists in the non-app group. This may be because the application stimulates better acquisition of the dependent shared knowledge, structure of which is somewhat discovered with the app, while without its support knowledge gaps remain unbridged and the solutions to these different questions appear disconnected to the students.

To complete this association analysis We further depicted the associations among the incorrect answers chosen by the students of the 2 groups in the 9 questions as shown in Fig. 12. The index of each question is highlighted in green beside the rectangle corresponding to the question. The 3 choices represented using dots are listed inside the rectangle of each question. The dot highlighted in red marks the correct answers, while the other 2 are errors. The links in the figure show the associations among the error choices of different questions. Similarly as in Fig. 10, there are significantly fewer associations in the app group than in the non-app group, indicating better understanding and learning performance of the students who used the application. Interestingly the gaps causing specific type 2 error in the question 2 within non-app group appear to be impacting on making many other correlated errors in other questions. Moreover, type 3 error in the question 7 appears to be a compounded result of the gaps evidence from many other incorrectly answered questions in the same group. No such strong error dependencies appear in the app group.

Course providers can take advantages of such extracted association rules that not only discover a hidden relationship among the dependent co-shared knowledge elements, but also reveal the apparent nature (summary or specific) and the difficulty of the assessment questions and inform about the student knowledge gaps pointing at the possibility of restructuring of the teaching material to offer prioritized and personalized



(a) No-app group (b) App group

Fig. 12. Association among error answers of each question in both groups.

support to most efficiently bridge these gaps. The biggest beneficiaries of such revealed insight could be the growing base of e-learning course providers that could eventually exploit such feedback to autonomously and continuously adapt the taught content to maximize learning efficiency and boost students focus and motivation for using it.

E. Survey Analysis

After completing the quiz, we invited the students from the non-app group to try the AIR-EDUTECH and together with the app group students complete a short survey to capture their feedback and evaluate their experience of using it.

The survey was split into 2 parts: the first part comprised 12 multiple-choice questions asking about the feedback on using technology like the AIR-EDUTECH in education, and the second part included just 2 short questions asking for students' opinion and suggestions on the application improvement.

The results of the 12 questions in the survey are shown in Fig. 13. Although out of 70.6% of students participating in the survey rarely used advanced technology during their study and only 32.4% downloaded education applications on their tablets in the past, all students prefer using such technology more often in education. This indicates a strong demand on effective and impactful applications of advanced technologies in education, should they, like our AIR-EDUTECH prove to be fun, engaging and offering instant educational benefits.

The feedback on application evaluation indicates that most students were satisfied with the application, among which 88.2% strongly agreed that the application was easy to use and had clear content. All students agreed (67.6% strong agreed) that AR would be a good addition to the learning process. 100% of them would recommend such an application to their friends and classmates because it can help them comprehend the subject better. Some students even suggested scaling up the application to include more elements and having the application as a permanent supplement to their existing text books. Unsurprisingly, all students rated the application as excellent, indicating its successful trial and opening a great prospective opportunities for technology-enhanced learning.

Detailed understanding of the most influential features of the system and the structure of their isolated impact on learning performance requires a separate dedicated research itself. However, Within the realm of our limited study and subject to the limitations of the collected data we only attempt to draw the preliminary conclusions based on answers to our open-ended survey question of "What was the most appealing feature in the application?".

The feedback provided by students indicates that the AR/AIR features of the AIR-EDUTECH such as engaging physical interaction with the system through colliding cards, spatial interaction and visualization of structures of compounds/elements with 3D models, helped them to better understand abstract concepts. Specifically, we highlight very important role of rich multimedia content (e.g. audio, video, 2D/3D image, 3D models' visualization, etc.) which not only provides supplementary explanatory content during the crucial moments of the thought process in which they attempt to understand and absorb new knowledge by reconciling it with their current knowledge, but also acts as a catalyst to help isolate students' exclusive attention during this act and fully channel their focus to the task at hand. The students confirmed in the survey that they found the audio played in the system very useful in helping them remember the names of the molecules. Amusement features combining sound, 3D models, character, images, etc. created an interactive, immersive and entertaining environment that helped to attract their attention and enhance the motivation for learning. Interactivity with real world (e.g. collision, spatial interaction, virtual buttons) helps to improve students' understanding by touching and experiencing the taught content, e.g. doing virtual experiments by using the cards representing substances or elements to trigger chemical reactions, or visualizing molecular sphere-and-stick models with 3D animation via interaction using cards with corresponding molecules, improving efficiency of traditional classroom learning that critically depends on students' abstract thinking ability and experimental experience. The application intends to resemble a virtual chemistry lab to help in overcoming the drawbacks of hands-on labs such as availability, cost, the risks of adverse effects, etc. Connection with real objects/environment through physical cards makes the virtual experience more real and interesting.

F. Discussion

Chemistry is broadly considered a difficult subject for students. As many researchers, teachers and science educators point out, the abstract nature of many chemical concepts stems from even more complex blend of underpinning higher

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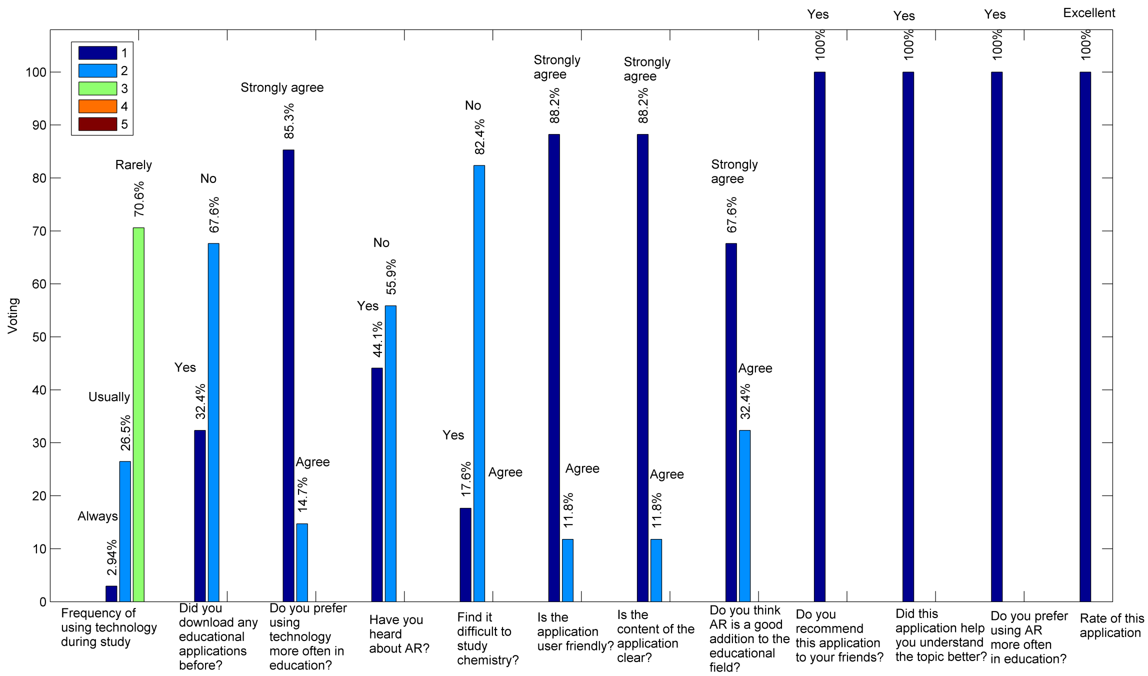

Fig. 13. Results of the survey.

maths, complex algebra, nuclear and quantum physics, which jointly are able to explain chemical processes but remain typical out of reach for students at the time chemistry is taught and hence prevent them from developing deep intuitive and complete understanding of of this subject. Therefore any additional support, especially tech-infused aid utilizing multi-modal explanations, engaging simultaneously multiple human sensors are expected to effectively bridge this complexity gap through enriched immersive experience, fully focused and isolated mind engagement and simply much widened bandwidth of information transfer. There in general are three types of learners: listening, seeing and touch/experience learners. It is our observation of much higher learning efficiency achieved when exposed to high bandwidth multi-sensory inputs, that inspired us to develop the AIR-EDUTECH system, that as we hypothesize, thanks to rich AIR features managed to combine multiple human sensory inputs to help students absorb chemical knowledge more effectively, more broadly and in a fully engaging, interactive yet more fun and entertaining format, in which students seamlessly learn and retain much more chemical course content than in a traditional setup.

In the above sub-sections, the impact of the AIR-EDUTECH has been quantitatively evaluated using various statistics and data mining methods. To determine if the AIR-EDUTECH can help to improve learning performance, the learning results of app and non-app groups have been compared. To ensure the comparison was fair and agnostic to other impacts but the sheer utility of the application in the learning session, all of the other conditions were fixed similar for both groups including the teacher, taught content, students' gender, numbers and their academic performance composition.

The critical evidence extracted from the field study was provided by the results of the short quiz carried out in both groups after the teaching session to evaluate students' understanding and retention of the taught content. It allowed to directly measure the isolated impact of AIR-EDUTECH support on learning performance by comparing the results achieved by the two groups with all other group characteristics fixed the same. Although only the effect of one-time use of the system was evaluated, comprehensive analysis in various aspects has shown statistically significant gains in the retained chemistry knowledge that appear consistent across differently performing students and grow even further with the increasing complexity of the taught content.

In further research, we will try to extend the AIR-EDUTECH application exposure to the whole grade 11 chemistry syllabus, and introduce it to other subjects, e.g. physics. Such extended and more diverse field study with many more students might open for interesting new research avenues that may include the impact of student gender and their mix in the groups, the impact on long-term knowledge retention etc.

VI. Conclusions

This work intends to identify and characterize the impact of the application of AR/AIR technologies in education, specifically, to determine if they have the potential to improve learning performance. An educational mobile system, code-named as AIR-EDUTECH, has been developed based on AIR technologies to help high school students learn chemistry in an augmented and interactive environment enriched by variety of multimedia content including 3D animated molecular models. The results from the field study conducted on the sample of 45 female students in the 11^{th} grade chemistry class, showed the students who used the AIR-EDUTECH in learning

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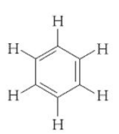
chemistry scored much higher in the subsequent assessment quiz, compared to the students who followed traditional learning. Comprehensive quantitative analysis of the results has been carried out to gain deeper understanding of the nature and the impact of the AIR-EDUTECH system. The analysis involved attainment distributions, statistical significance tests and association rules mining over relationships between correctly and incorrectly answered questions, and it comprehensively validated the positive impact of the introduced AIR-EDUTECH application. Since AIR technology was a critical component differentiating AIR-EDUTECH from many other apps on the market we conjecture that AIR technology is most likely responsible for the bulk of learning improvements and knowledge retention gains we have demonstrated in our case study. Nevertheless, we acknowledge here that wider scale trials with more diverse students and knowledge content are required to better isolate the sheer AIR technology impact on learning performance, to precisely measure the magnitude of this impact and thereby to quantitatively prove AIR technology brings a positive impact on learning performance.

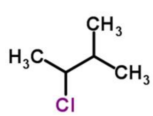
Our study additionally revealed several other interesting insights. Among those possibly the most important was the capability of the system to provide compounded improvements for the most complex content and discover critical knowledge components that if neglected may lead to deep knowledge gaps among students. As we have shown, such gaps can be easily discovered and bridged with the AIR-EDUTECH. In summary, the comprehensively positive results obtained in this trial give a great prospect of similar benefits of AIR technology to be replicated across other education curricula.

Appendix A
Short Quiz

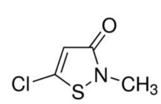
1) Which of the following is Benzene?



(a)

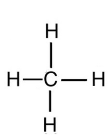


(b)

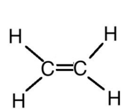


(c)

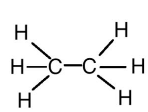
2) Which of the following is made using Ethanol CH_3CH_2OH?
   A. Paper B. Soaps C. Perfumes
3) Which of the following contains Carbon Dioxide CO_2?
   A. Oil B. Fire extinguisher C. Plastic
4) Which of the following is used in manufacturing plastic?
   A. Carbon Dioxide CO_2 B. Ethylene C_2H_4 C. Water H_2O
5) Which of the following is Methane?



(d)



(e)



(f)

6) Salt is ....?
   A. NaCl B. NaOH C. Na_2O_2
7) $2H_2O+2Cl_2$->..........+..........?
   A. $4HCL+O_2$ B. $NaOH+O_2$ C. Na+HCl
8) $2HCl_2+O_2$->$2Cl_2O$+..........?
   A. H_2 B. O_2 C. HCl_2
9) NaOH is a strong chemical base usually used in..........?
   A. Soaps and detergents B. Glass C. Food

Appendix A
Survey

- Using technology in education:
  1) How often do you use technology during your study
     A. Always B. Usually C. Rarely D. Never
  2) Did you download any educational applications on your tablet before?
     A. Yes B. No
  3) Do you prefer using technology more often in education?
     A. Strongly agree B. Agree C. Neutral D. Disagree
  4) Do you prefer using technology more often in education?
     A. Strongly agree B. Agree C. Neutral D. Disagree E. Strongly disagree
  5) Have you heard about augmented reality (AR) technology?
     A. Yes B. No
  6) Have you heard about augmented reality (AR) technology?
     A. Yes B. No
  7) Have you heard about augmented reality (AR) technology?
     A. Yes B. No
  8) Do you find it difficult to study chemistry using traditional methods?
     A. Yes B. No
- Application evaluation:
  1) Is the application user friendly (easy to use)?
     A. Strongly agree B. Agree C. Neutral D. Disagree E. Strongly disagree
  2) Is the content of the application clear?
     A. Strongly agree B. Agree C. Neutral D. Disagree E. Strongly disagree
  3) Do you think that Augmented Reality is a good addition to the educational field?
     A. Strongly agree B. Agree C. Neutral D. Disagree E. Strongly disagree
  4) Do you recommend this application to your friends?
     A. Yes B. No
  5) Did this application help you understand the presented topic better?
     A. Yes B. No
  6) Do you prefer using augmented reality technology more often in education?
     A. Yes B. No
  7) What is your rating of this application?

A. Excellent B. Very good C. Good D. Acceptable

- Your opinion, suggestions, and notes regarding the application?
- What was the most appealing feature in the application?

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