Development of a Virtual Laboratory Experiment for Biology

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Abstract

Computer-based virtual simulation is being widely used for the purposes of education and skills training. These include special needs education to sophisticate teaching aids in high schools and universities for the delivery of medical and scientific education. This project investigates the issues in the development of virtual learning environments (VLEs) in the teaching of biology to students in a university Life Sciences department, focussing on a laboratory experiment in an immunology module.

To explore the potential of VLE in learning concepts, principles, and laboratory skills from experiential of virtual experimental exercise, this paper discusses the process of the development of VLE as a self-learning package. A set of design strategies is proposed to guide the design of VLE. An important feature of the VLE is to employ virtual tutoring agents to scaffold the learning process in order to ensure the important learning tasks are tackled. The virtual agents monitor the student's actions and provide advice in the learning process once a mistake of sequential procedures occurs. The students can carry out non-sequential procedures in their own way. Formative evaluation studies were iteratively carried out with the target students to improve the design of VLE. The evaluation results show that the participants were satisfied with the VLE.

Keywords

virtual reality, virtual learning environment for education, virtual learning environment for training laboratory skills, virtual tutoring agents, virtual simulation in biology, E-learning for biology.

Introduction

Learning in biological science is a combination of understanding, conceptualisation and practical experience. Visualisation and conduct of laboratory experiments are the most effective ways to simplify and clarify the comprehension of complex theory. However, there are inconveniences with these traditional educational methods due to the constraints of geography, time schedule, supervision, materials and cost. Computer-based virtual learning environments open new realms in the teaching, learning and practice of the Life Sciences. Virtual learning environments provide students with the opportunity to achieve learning goals, without some of the mentioned constraints above. VLE-based applications have thus emerged in mainstream education in schools and universities as successful tools to supplement traditional teaching methods.

Virtual learning environments provide three-dimensional (3D) graphic insights into the structures and functions of biological systems. Students can thereby learn the principles of a biological system in a fast, effective and pleasurable way by interacting with and navigating through the VLEs (Amon, 1999).

Virtual Learning Environments in Biology

The goal of biological education is to teach students a framework of basic principles and approaches that can later be used to solve biology-based problems. For students to have a successful educational experience, they must master the content of a discipline. The challenge in biology-based education is to employ educational methods that deliver both the basic principles and the important content material in a meaningful way. Virtual learning environments achieve these goals by providing students with3D virtual environments, allowing them to interact with virtual objects and immediately gain results of the actions on the screen display. Presenting biological educational material via computer-based virtual reality systems significantly affects how, and to what depth, principles and content are available to students.

Researchers have made major advances in the design of VLE for applications in microstructure, anatomy and clinical-related systems. These VLE-based applications cross a wide of range of applications from medical and surgical training to biology and specialist areas such as immunology (the field of biology concerned with the ability of the body to fight disease) and offer students different levels in navigating and interacting with the VLEs (Novak, 1998; Pichumani, 1998).

A blood vessel, cell and protein models, and lymph node have been continuously simulated in 3D virtual environments. Students are free to explore these blood vessels, cell and protein models, and lymph nodes by piloting a small "nanobot" ship (Dean, 2000). A typical cell environment was constructed at NDSU (North Dakota State University). The virtual cell contains 3D representations of all the components and organelles of a cell such as the nucleus, mitochondria, and chloroplasts. Students learn the structure and functions of a cell by interactively performing goal-oriented tasks in the 3D virtual cell (White, 1999).

In the virtual biology laboratory designed at the State University of New Jersey, students can practice biology related experiments. For example, the students can discover the cell mitosis and meiosis, and practice skills of centrifuging liquid (Subramanian, 2001).A set of biology laboratory exercises is offered at the Howard Hughes Medical Institute in USA. A Bio-Interactive, a collection of learning modules, has been developed, which allows students interactively to explore topics in cardiology, neurophysiology and immune system. These virtual exercises augment neuroscience laboratories (Howard Hughes, 2003).

VR based environments could be used in the simulation of anatomy to train students and surgeons and study anatomical structures. The applications help students in the visualisation of organs, functional analysis and study of organ movement. In a virtual environment, a human body can be considered as a structure formed by a number of segments that are united by different types of joints. These segments represent relative movement between each other. Students discover the physical properties and kinetics of the segments. Students can interactively assemble and disassemble the human skeleton to explore how each segment attaches itself to the other (Hattori, 1998; Hoffman, 1999; Hilal, 1998; Liu, 2002). Some complex organs such as the brain and heart, which are difficult to explore in the real world, can be constructed in virtual environments and divided into several parts. The students can open each part to inspect the structure inside and outside from different viewpoints (Sato, 1998; Robb, 1998). In another example, a complex VR model of a heart has been designed. Students can rotate it, move it, zoom in for details or even fly through it. It can be explored during the cardiac cycle to help understand its function. A transparency mode demonstrates the coronary arteries, movement of the heart valves, and blood-flow (Friedl, 2002). An advanced virtual simulation of brain has been recently created at the Nottingham University. The simulation could be used to train surgeons to a much higher level before they get to the operating theatre, making surgery safer for patients with less risk of complications. The virtual brain allows the surgeon to "feel" as though they are actually touching the brain while they 'operate' (Vloeberghs, 2004).

Both learners and educators have the potential to benefit tremendously from the use of VLEs. However, few research programmes in virtual reality have concerned themselves with the experimental aspects of the biological field. Here we describe the development of a virtual laboratory-based experiment in immunology, in which practical classes illustrate the important biological principles, viz. Single Radial Immunodiffusion has been replicated in a virtual laboratory environment. The students can carry out the virtual exercises in their own way. The virtual tutoring agents are employed as a design strategy and monitor the students' actions to ensure the learning tasks tackled.

Design strategies

To be an effective skills-based training tool, a good courseware product should be made up of three components: educational software, instructional support and learning motivation. The structure of the virtual laboratory experiment was designed to be goal oriented, engaging, attractive, interactive and flexible. These features demonstrate the ability of VLE in learning and reinforcing knowledge from experiential of carrying out virtual exercises in the virtual laboratory. To achieve these educational goals, these design strategies were set as guidelines in the development of the virtual laboratory experiment.

Goal - oriented

Students gain knowledge and experience by completing the laboratory exercises in the virtual environment. The students improve their experimental skills by controlling and interacting with the objects and equipment in the virtual laboratory as they would in a real laboratory. The operations embody the real laboratory tutorial goals. If the students make a mistake, an embedded tutoring agent displays a message to scaffold the actions of the students, and gently correct them onto the correct learning path again.

Learning by doing

Virtual environments give students meaningful, near-real experience and illustrate important concepts, principles and procedures. Students gain a deep understanding by prompting, correcting and repeating the procedures they have previously undertaken incorrectly. Students carry out a self-paced exploration of the experiment, where they can make observations, manipulate the interactive objects, and perform experimental procedures. Doing an experiment in a VLE incarnates the rule of "learning by doing" (Anido, 2005; White, 1999). Experiences are the best teachers (Slator, 1999).

Interactive

Interacting with objects in virtual environments is a key feature. A successful virtual environment is one that engages users, encourages users' participation and evokes a feeling of presence in the virtual world. In order to produce a feeling of presence in the virtual world, a simulation should be capable of real-time interactivity, which gives users immediate feedback.

Flexibility

The flexibility of interaction with the objects in the virtual environment is a key factor for attractive applications, which allows students freely to interact with the objects in ways they like. However, a potential dilemma in the promotion of experiential learning emerges. If learners are allowed free exploration of these VLEs, how can it be ensured that the target learning objectives are achieved? How can it be ensured that learners carry out the necessary activities that will allow the construction of knowledge through their experiences if they are free to carry out some activities and ignore others? Empowerment in the form of free exploration to construct knowledge through interaction with realistic objects and activities should be tempered by the introduction of some form of control (educational strategies) to ensure that the necessary lessons are learned (Cromby, 1996). For this skills-based training application, an intelligent tutoring agent system is employed to scaffold the important activities. Introducing virtual tutoring agents reduces the flexibility of the virtual simulation. However, it is necessary to ensure the learning tasks to be tackled.

Intelligent tutoring agents

The intelligent tutoring agents are analogous to human tutors. The virtual tutors monitor students' actions. They offer advice in the formats of a text-based message, voice or video for students to correct their mistakes in the learning process, but these should not be issued as directives.

Development of virtual laboratory experiment

Principle of the simulated laboratory experiment

The virtual laboratory experiment demonstrates the concepts and principles of a classical immunological technique called Single Radial Immunodiffusion, which occurs following the specific interaction between an antibody (a protein which forms part of the body's defence mechanism) and an antigen (detected as being a substance which is "foreign" to the body). In this experiment, the antibody is mixed with liquid agar gel, and the antigen (an enzyme called amylase is used in this example) is loaded into cavities (wells) in the agar gel. The antigens then diffuse into the surrounding antibody-containing gel. When the concentrations of antigen molecules and antibody molecules are at equivalence (a ratio of 1:1), the antibody interacts with and precipitates the antigen out of solution. At this point, the antibody-antigen complex forms an immunoprecipitation "halo" or ring around the well. The ring diameter is related to the antigen concentration originally placed into the well. Therefore, various concentrations of a purified antigen ("standards") can be used to establish a standard calibration graph so that the unknown concentration of antigen in biological fluids can be determined. In this experiment the concentration of amylase in saliva is the parameters to be determined; a range of amylase concentrations ("standards") are prepared by dilution of a concentrated amylase solution.

Design of the virtual laboratory experiment

Based on the goal-oriented design strategy, the students gain knowledge from the experiential of completing laboratory experiment. The virtual laboratory experiment should convey the information that the students need to master and refer to in the learning process. Examining the contents delivered by the virtual laboratory experiment, they are divided into text-based explanation, video demonstration of the procedures, plotting experimental results, learning outcome test, and interactively carrying out the laboratory experiment in a 3D virtual environment. To make use of both the features of 2D and 3D Windows, 2D and 3D Windows applications are employed to present these different types of learning materials in the virtual laboratory simulations. The 2D Windows applications include an introduction Window, help system and plotting Window for different learning goals. The 3D virtual environment provides students with realistic and interactive visual images and is used to simulate the laboratory in which the students can practise experimental skills.

Introduction Window

The introduction Window (Figure 1.) gives an instruction of how to use the virtual laboratory. Following this instruction, the students can access the help system, launch the 3D virtual laboratory, and exit the introduction Window by clicking on a button.

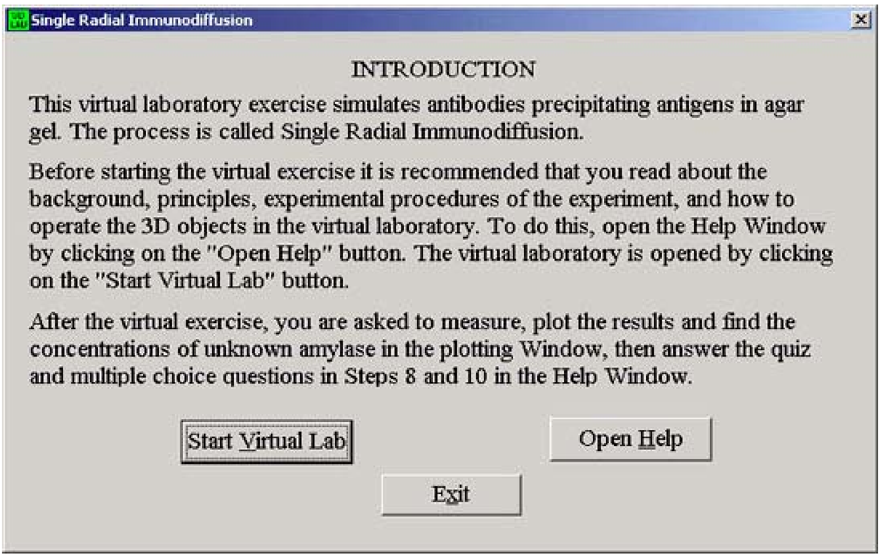

Figure 1. Introduction Window

Three-dimensional virtual laboratory

The 3D virtual environment (Figure 2.) provides the students with 3D objects that make up the equipment in the virtual laboratory need to be user-controlled in order to carry out the virtual experiment. The 3D objects are divided into operable and non-operable objects. Students can select one operable object at a time and manipulate it to complete a virtual experimental procedure.

The experimental procedures are designed based on the laboratory tutorial developed at the Nottingham Trent University in UK (Billett, 2000). In a real laboratory, some procedures are restricted to be carried out in a sequential order to ensure the experiment successful, which is called **sequential procedures**. For example, the amylase liquid should be diluted from the tube to the left of the current tube. The others can be in free order, which are called **non-sequential procedures**. In the virtual laboratory, the sequential procedures are monitored by the virtual tutoring agents to ensure that the learning tasks are tackled. The non-sequential procedures can be freely carried out, even broken by the other procedures and resumed later, to give the students flexible choice in completion of these procedures.

Figure 2. Three-dimensional virtual laboratory

Plotting Window

To understand the utility of the principles of the laboratory experiment in real life, a plotting Window (Figure 3.) follows the virtual exercises for processing the virtual experimental results. The plotting Window is programmed for measuring the experimental results, plotting standard amylase line and finding the unknown amylase concentrations in the samples of saliva. The plotting Window is divided into two panes, drawing and data panes, for measuring and plotting the experimental results, and recording data. The students can then measure the experimental results, plot the resultant line and find required results.

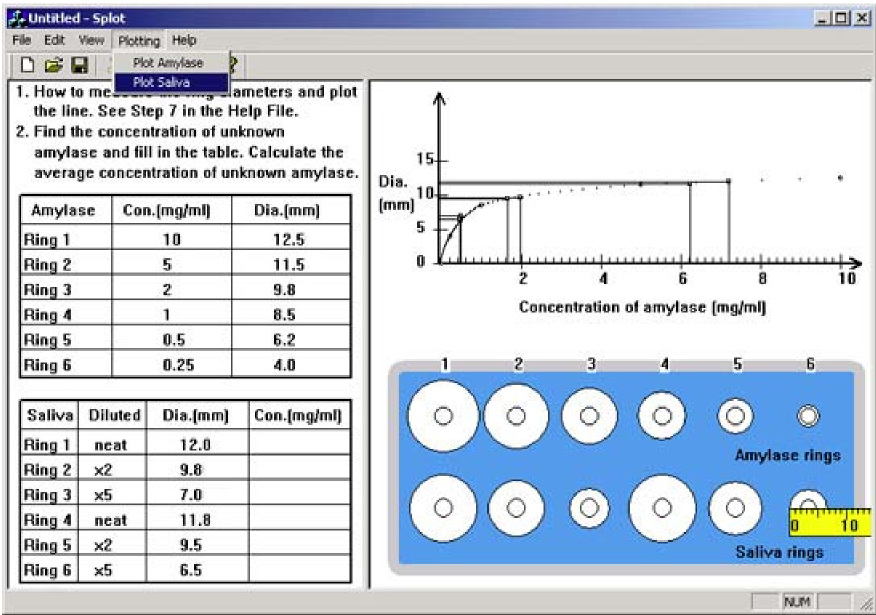

Figure 3. Plotting Window

Help system

Since the students may require help in different aspects when they carry out the virtual laboratory experiment, a Help system (Figure 4.) is created to contain information regarding the background, concepts and principles of the laboratory experiment, instructions for carrying out procedures and the rules of operating the objects in the virtual laboratory. A quiz and a set of multiple-choice questionnaire included at the end to test the learning outcomes. The students could reinforce their knowledge by doing the test. This may give an indication of their ability to generalise this knowledge to a real world competency.

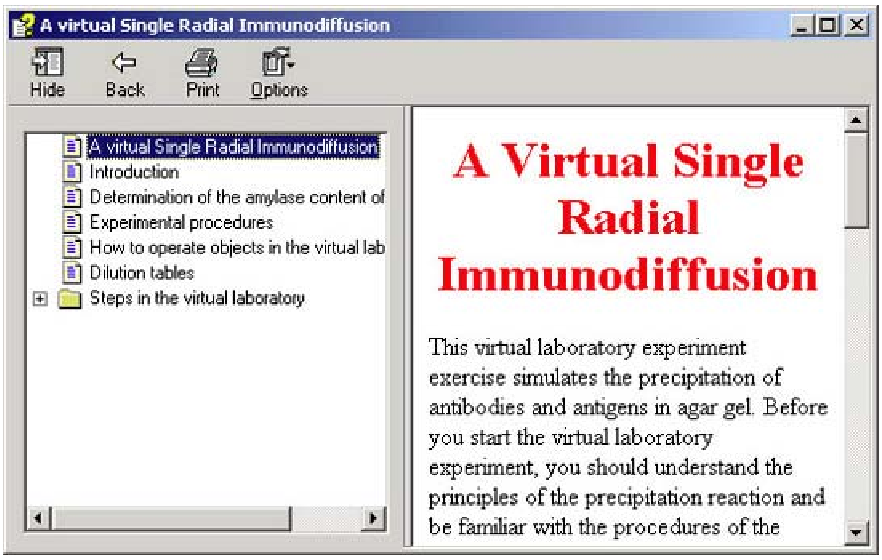

Figure 4. Help Window

Development of virtual tutoring agents

The development of a set of intelligent tutoring agents is a key goal of this project. One of the aims of this research project is to focus on the development and implementation of intelligent tutoring agents to provide effective and "scaffolded" learning experiences for students. An intelligent agent is a section of computer programme that simulates a human relationship by doing something that another person could do (Seiker, 1994).These virtual tutoring agents should support models of knowledge of an expert, instructor or teacher. Three types of intelligent tutoring agents are investigated in the virtual laboratory.

Deductive tutor

provides assistance to students in the course of their deduction with scientific problem solving, which is required to accomplish their tutorial. For example, if students add a certain liquid to a tube, but instead they select a wrong tube, the deductive tutor will display a warning message and play an audio track to the students.

Rule-based tutor

provides assistance to students by:

- Encoding a set of rules of an experiment.
- Monitoring a student's action and looking for one of these rules to be "broken".
- "Visiting" students to present expert advice.

For example, there are dilution rules: (1) the amylase in tube 1 should be diluted from the Amylase bottle (the first bottle from left in Figure 2) and (2) the amylase in tubes 2 to 6 should be diluted from the tube to the left of the current one. If the students break one of the dilution rules, the rule-based tutor will remind them. It also tells students where to find a relevant case-based virtual tutor for demonstration.

Case-based tutor

provides assistance to students by presenting an example of closest relevant experience. For example, a video for each experimental procedure is embedded in the virtual step in the Help system.

The deductive and rule-based tutoring agents are embedded in the 3D virtual environment to monitor student's actions and record the status of the objects in the learning process to ensure the learning tasks tackled. A virtual agent provides the students with advice once the students make a mistake, overlook an object or break a rule, which result in the experimental progress toward successful completion impasse. The advice is designed in both text and voice message formats for greater accessibility.

The case-based virtual agents are embedded in the Help system in order to reduce the working load of the 3D virtual laboratory. The case-based virtual agents play a video stream to demonstrate a procedure of the experiment once a request is explicitly made.

Evaluation

Evaluation is concerned with gathering data about a design from a specified group of users for a particular activity within a specified environment or work context. The evaluation provides answers to questions that inform the iterative design, and forms an integral part of the development of a system. The evaluation programme is interesting in getting feedback of the "what do you think of this idea?" The distilled information from evaluation studies is fed into the next refinement to improve the system and assess whether the system reaches the users' needs. In this way, evaluation meshes closely with design process and improves the product by providing feedback. For this reason, this kind of evaluation is called formative evaluation (Preece, 1998).

For a system, more than two methods may be combined together, which could give extra confidence of the result accuracy by concurrency of data produced from these evaluation methods (Preece, 1998). The methods of questionnaire survey, interview and observation are used in the evaluation of the virtual laboratory experiment. The aims of the evaluation are to assess any existing problems in user interface design and the simulated contents, the usability, the need of the virtual tutoring agent, target users' attitudes and to debug the programmed functions. Identified problems are corrected to improve the virtual laboratory experiment until the students are satisfied with the products.

Method of the evaluation of the virtual laboratory experiment

Participants: The evaluation studies took place in Life Sciences Department at the Nottingham Trent University in UK. Twenty-seven target users were invited to evaluate the virtual laboratory experiment. They were students who were currently taking the immunology module. A criterion of selection of these target students included that they are novices in using the 3D virtual laboratory experiment. Details of the participants are shown in Table 1.

Table 1. Profile of participants

Profile	**Description**
Age	18 – 19 years old
Sex (male: female)	15:12
Ethnicity	British
Motor Skills Abilities	Can use the mouse and keyboard for interaction.
Language	English is used in their immunology module.
Educational background	Undertaking a UK-based University degree in Biology or Biological-related sc
Extent of expertise	Undergraduate science students with knowledge of biology and immunology r
IT skills	The participants are familiar with the use of the mouse, keyboard, monitor, a normal tasks, such as using Microsoft Word for writing and editing documents
Training they have received on using the 3D virtual environments	The participants are novices in using this 3D virtual simulation.

Measures: A questionnaire survey was used to collect evaluation data from the participants. The observation and interview were used in conjunction with the questionnaire survey as data collection methods.

Procedure: The evaluation study was carried out in five iteration cycles with the participants. The number of participants in the five evaluation iterations is 5, 6, 4, 8 and 4 persons respectively. The designer observed and recorded the participants' behaviour without any additional interference. There was no time limitation for completing the virtual exercise. The participants could choose to withdraw from the evaluation study at anytime they wished. Their data was kept confidential.

Analysis of the results of the questionnaire survey

In each evaluation iteration, the participants were asked to rate the questions posed by giving a numerical value from 1 to 5. The values 1 to 5 are for a negative to positive response. The mid-point is the value of 3. The sum of the numerical values for each question is divided by the number of participants in each evaluation iteration to give the mean value, which is called the observed mean value.

The numerical values greater than the mid-point value are considered as positive attitudes expressed by the participants and those less than the mid-point value as negative attitudes. When the observed mean value is greater than the mid-point value, the participants are judged to be satisfied with the evaluated aspect of virtual laboratory experiment. The results of the five evaluation iterations are presented in Table 2. The discussion of the results follows Table 2.

Table 2. Results of evaluation from the questionnaire survey

No.	**Interaction/Tasks**	**Rating scale values**	**Observed mean values in the five evaluations** 1st 2nd 3rd 4th 5th	**Values at the mid-point**
1	Flexibility of procedures in the virtual laboratory is	Flexible (5) to Inflexible (1)	3.0 3.2 4.1 4.3 4.2	3
2	Operating objects in the virtual laboratory is:	Easy (5) to Difficult (1)	3.0 3.7 4.3 4.3 4.8	
3	Virtual tutoring agents are:	Helpful (5) to Annoying (1)	4.5 4.7 5.0 4.6 4.8	
4	Measuring the ring diameters is:	Easy (5) to Difficult (1)	4.6 4.5 4.8 4.9 5.0	
5	Plotting the amylase line and finding the amylase content of saliva in the plotting Window is:	Easy (5) to Difficult (1)	4.0 4.7 4.6 3.5 5.0	
6	Is the virtual simulation helpful in understanding the concepts and principles of Single Immunodiffusion?	Helpful (5) to Unhelpful (1)	4.2 4.3 4.2 4.8 4.8	
7	Have you carried out the experiment in a real laboratory before? If so, how do you feel when using the virtual simulation:	Comfortable (5) to Uncomfortable (1)	4.4 4.2 4.7 4.3 4.8	

Question 1 is to evaluate the flexibility. The feedback indicates that the flexibility is a prime requirement in the first two evaluation prototypes. In the refined prototypes, consideration of increased flexibility receives significant focus. The sequential procedures are monitored by the virtual tutoring agents to ensure the learning tasks are tackled. The virtual tutoring agents record the status of a variety of 3D objects. The

virtual tutoring agents analyse what has been done and what has not been done by checking the status of these 3D objects. If the sequential procedures are carried out incorrectly, the virtual tutoring agents will stop the participants and give them a chance to rectify their errors and repeat their actions. The non-sequential procedures can be carried out in any order to offer the participants more flexible options. The participants responded to this with better rating values in the third, fourth and fifth evaluation iterations. The observed mean values are greater than the mid-point value. It indicates that the participants were satisfied with the increased flexibility of the virtual simulation.

The process of scaffolding the sequential procedures by the use of virtual tutoring agents does not offer the participants fully free exploration. The virtual tutoring agents create constraints in terms of flexibly carrying out virtual exercises in the 3D virtual environments, but they are necessary to ensure the learning tasks are tackled and feedback given appropriately. It is a trade-off between flexibility and ensuring that the learning tasks are tackled and the students gain the experience from practising the virtual exercise, which has been discussed in the "Flexibility strategy".

Question 2 "Operating Objects in the virtual laboratory", raises problems encountered by the participants in the first evaluation iteration. A set of operation rules for manipulating the objects is defined in the virtual simulation. Since the participants are novice in using this 3D virtual training package, these rules are listed in the Help system. It was observed that the participants deal very well with the operations in the virtual laboratory if they first carefully read the operation rules. These participants spent less time in completion of the virtual exercises than those who did not first read the rules. Feedback from participants in the interview revealed that they could more easily perform tasks in the virtual laboratory after they were familiar with the interaction possibilities within the 3D environments and with the virtual objects. Noticing that reading the operation rules and taking a practice session before attempting the experiment was of benefit to the participants, the participants were, from then on, reminded to first read the operation rules carefully and take a pre-practice in the later evaluation iterations. The participants could easily complete the virtual exercises and responded well in the later evaluation iterations. However, reading the Help system and undertaking a pre-practice are left as optional since the participants have different levels of computer skills and experience of using 3D applications.

Question 3 is to evaluate the usefulness of the virtual tutoring agents in the learning process. The participants gave very good feedback regarding the help from the virtual agents. It indicates that the virtual tutoring agents could be competent to provide the participants with help and ensure the learning tasks tackled by analogy of human tutors in the virtual learning process.

Questions 4 to 5 are to evaluate the usability of plotting Window. The participants gave very positive feedback, which indicated that the participants were very satisfied with the usability of the plotting Window in terms of measuring the ring diameters, plotting and finding the results of amylase. However, in the fourth evaluation iteration, some participants argued that the scale on the x axis was too big to read comfortably, which resulted in lower observed mean value. The scale on x axis was refined to the reading of tenths (see Figure 3.). The participants gave very good response to this question in the fifth evaluation iteration.

Questions 6 and 7 are to solicit the participants' opinion regarding the use of the virtual laboratory experiment. The feedback from the five evaluation iterations indicates that the virtual simulation is helpful in practising experimental skills and in understanding the underlying concepts and principles of immunology. Since the virtual tutoring agents analogise the performance of human tutors to scaffold the sequential procedures, the participants can avoid improper operations, fatal mistakes, and are free from peer pressure. The participants felt more comfortable to conduct the experimental exercises within the virtual laboratory than in a real laboratory. They gave very positive response to these questions.

Analysis of the results of observation

It was observed that the participants enjoyed using the virtual laboratory experiment. However, some participants encountered a problem with operating the 3D virtual objects and required help on how to control the virtual objects at the beginning of the virtual laboratory exercise. Reminding the participants to first read the operation rules in the Help system and giving them a chance to pre-practise the operation, the problem was effectively overcome.

Analysis of the results of interview

The participants were interviewed and given the opportunity to present verbal feedback after completing the virtual exercise, but not all of the participants gave feedback. The participants commented that the virtual laboratory experiment is intuitive to use, and helpful in allowing students to gain an understanding of the underlying biological concepts and principles of immunology, and in learning the procedures of the experiment. The plotting Window was found to be very easy to use for plotting amylase results and finding the unknown amylase concentrations in the saliva samples, which helps them to understand the usage of the Single Radial Immunodiffusion experiment in real life. The quiz and multiple-choice questions reinforce the knowledge of immunology and usage of the laboratory experiment in real life. The virtual tutoring agents were found to be a helpful aid to complete the learning tasks.

Not withstanding, some participants suggested refining the coordinate scales in the plotting Window more accurate in order to make reading results easier.

Conclusion

Computer-based virtual learning environment is a relatively new technology in education and training. Studies to date have shown VLEs potentially benefits both educators and students, particularly in higher education and in the delivery of complex scientific concepts and principles. It eliminates time and geographical constraints. At the moment, such applications would not replace real world laboratory exercises. Students, however, could augment their real life laboratory experience. They can explore the virtual laboratory experiments in a relaxed and flexible environment at their own speed and need. They can use it at revision time, when access to the real laboratory may be prohibited in an unsupervised way, due to the expensive or dangerous nature of the laboratory exercises. Educators can add to their battery of course materials to promote more effective understanding of curricula, and more easily accessible course resource.

From questionnaire and observation data analysis, the evaluation study indicates that the performance of virtual laboratory experiment satisfies the end users' requirements. The verbal feedback in the interview supports the results of questionnaire and observation. The same results gathered from different evaluation methods verify the consistence and reliability of the evaluation feedback from the participants. The simulation of the virtual laboratory experiment is useful in immunology education. By completing the virtual experimental exercises and answering the quiz and multiple-choice questions, students could enhance knowledge retention. The virtual simulation technique is an effective and useful way for transferring knowledge and skills from the simulated virtual environments into physical reality. It encourages student's participation and incarnates the learning by doing rule.

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