Chapter 2
Use of Virtual-Reality in Teaching and Learning Molecular Biology

Sandra Tan and Russell Waugh

Abstract The teaching of Molecular Biology in secondary schools suffers from student disengagement and lack of suitable resources to help students master this novel area of their curriculum. The result is frustration and incomprehension by the students. Visualization is critical for the learning of Molecular Biology. While the traditional classroom uses diagrams, models, and other tools to accommodate visual-spatial learners, these tools are insufficient to represent the cellular and molecular dynamics elucidated by current research and presented in the modern biology classroom. Several works have recommended the use of simulation-based learning environments. This chapter describes the design considerations in formulating an approach to help students "see" DNA, proteins, and cellular structures in three-dimensional space. The experimental study and intervention described leverage on novel computer-based virtual-reality technologies to help students understand the three-dimensional structures and the molecular interactions between them that enable function. Results indicate significant increases in Molecular Biology achievement in male students. Focus group interviews reveal that, prior to this intervention, students relied heavily on memorization, and the visualization exercises helped to clarify understanding while increasing interest and engagement. The results of this study recommend the use of technology in the teaching and learning of Molecular Biology, especially for male students in Singapore.

Keywords Virtual-reality • Visual learning • Visualization • Molecular biology

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2.1 Introduction

The impetus for the present study on students' conceptions of Molecular Biology stems from recent changes to biology education in Singapore. Singapore's education system has been fundamentally driven by the needs of economic development [7, 13]. The most recent thrust to emerge has been the emphasis on life science research [4], a change that has percolated down from the tertiary institutions to junior college and high school curricula. The pace and depth of such changes, however, have caused the atmosphere in a Molecular Biology classroom to be one of disorientation, frustration, and resultantly incomprehension by students.

In this chapter, a research to investigate a solution to this problem is described. The study involved participants from several secondary schools in Singapore. They underwent a series of visualization exercises lessons in Molecular Biology. The research is conducted to explore whether the visualization exercises serve to increase participants' achievement in Molecular Biology, and the attendant skills that are important for understanding the subject.

The present study is also a project under the FutureSchools@Singapore initiative, as part of the Ministry of Education's Third Master plan for ICT in Education (2009–2014). The FutureSchools projects explore expanding learning possibilities, with Web-based and virtual learning environments that allow teacher–student interaction, online assessments, and monitoring of students' progress. Web 2.0 technologies, such as Wikis, video sharing, and Instant Messaging can expand the horizons of learning, allowing students to collaborate on projects among themselves as well as with peers from across the globe. The use of technology in schools, however, has not been objectively measured for effectiveness. In October 2011, a news story highlighted how executives working in technology companies such as Google and Microsoft were opting for traditional schools which eschewed technology; the view was that traditional schools allowed students to "experience" in a developmentally appropriate way [10]. A commentary in the local newspapers [12] also cited several cases of lack of assessment of technology use in the classroom, and even quoted a local teacher who discussed implementation of IT for its own sake without consideration for learning goals. Clearly, there is a need to objectively evaluate technology use in its different modes for specific teaching contexts, to address the concerns of various stakeholders in education.

2.2 The Research Design

2.2.1 Use of ICT

The design and use of visualization exercises on an ICT platform in the present study is informed by several empirical evidences and by the characteristics of today's students.

For example, in a study involving first-year medical students learning by virtual-reality (VR) experiences, Gutierrez et al. [11] described a positive effect of VR simulation on learning, as reflected by improvements in prescribed knowledge structures. More importantly, improvements demonstrated by the group given head-mounted display sets—where the three-dimensional (3D) visual experience was much more intense—were almost twice as large as the group relying only on computer screens in a partially immersive VR environment, and close to "expert" levels. Likewise, Barry et al. [5] described how the use of VR for exercise increased interest and engagement and increased the incidence of "flow", or energized focus, for reluctant exercise participants. Such positive reports of achievement and engagement provide a compelling suggestion for the use of simulation in Molecular Biology education.

Most previous studies to elucidate students' conceptions of specific areas of science have utilized "pencil-paper" illustrations [6] and diagnostic tests [17]. In light of the comfort of this generation of students as "technological natives" [18], the efficacy of visualization as a learning intervention for Molecular Biology might be enhanced if it occurs in a computer-based learning environment.

The use of ICT in the present study is in line with the characteristics of today's students. McHugh [14] discussed the characteristics of the new generation "iKid", whose whole life is dominated by cell phones, computers, and iPods and argued that the traditional teaching environment has lost touch with iKid's learning style. Similarly, Brevik [6] described the characteristics of these students as a generation experiencing "information overload". [19] Also agreed that there is discontinuity between learning styles of students today and the traditional classroom model. He named the students of today 'digital natives'—native "speakers" of the digital language of technology. While he made no reference to [14], [20] Implicitly agreed with both authors of this chapter and suggested that there have been recent trends in learning where students are living, learning, and working in a digital connected environment and students' learning styles are affected by daily exposure to technology. Technology, thus, plays a key role in the way students now learn and think. Recently, a new learning theory, connectivism [17], has emerged. This theory proposes learning to be a networked process. The connections of nodes of information are constantly evolving as students contribute to learning in collaborative online communities. This theory is relevant in explaining learning utilizing technology, where students are constantly exposed to text messaging, instant messaging, and other Web-based tools.

2.2.2 Consultation with Other Biology Teachers

A preliminary investigation was carried out to determine if visualization of Molecular Biology phenomenon was a prevalent problem among students.

Seven biology teachers from various schools in Singapore responded to a survey which sought their opinions on problems with students' conceptions of Molecular Biology. Some comments from teachers included, "students cannot 'see' how the different organelles in a cell function together…I have to show them several different pictures and hope they 'get it'" and "transcription and translation is a problem, since I have no way of showing students how the different molecules move in a complex".

Within the own classes of the first author of this chapter, the common complaint from students is that they are unable to "see" DNA and protein molecules on a 2D presentation, and thus cannot imagine the 3D structure and molecular interactions that enable cellular function. Most teachers and students welcomed the development of an addition resource that effectively communicated and represented the cellular and molecular dynamics of a cell, but also wondered if the use of such tools might lead to excessive investment of curriculum time on these topics.

2.2.3 Research Question on Computer-Based Immersive VR Visualization Exercises

The main research question guiding this study is "What are the effects of computer-based three-dimensional Molecular Biology visualization exercises on Molecular Biology achievement?"

Molecular visualization has now become a powerful tool in the biology and chemistry classroom [9, 16, 21]. In particular, interactive simulation-based learning environments for biology have developed rapidly in recent years. However, attempts to locate suitable simulation software and courses targeted at preuniversity levels have been unsuccessful. It appears unreasonable that postgraduate students are expected to be able to "plug-in" and to use and develop simulation tools for research when they have not been exposed to them in an instructional setting. This study represents possibly the first efforts to modify the existing research-based 3D simulation software for biology instruction at the secondary school level.

A series of computer-based immersive visualization exercises were developed as a proposed solution to the problem of student being unable to "see" cellular and subcellular level entities. A total of three large-scale VR modules were conceptualized and developed: (1) Cell organelles; (2) Protein making; and (3) Nuclear division. A VR Lab was set up in Hwa Chong Institution (HCI) in Singapore to enable the study. The VR Lab is equipped with a high-end projection system which is supported by a high performance VR workstation and a high-end interactive device. After a one-time calibration, the system can be used for multiple purposes in teaching, students' projects, and demonstrations. This setup of stereographic immersive and interactive 3D environment enables students to do visual learning and simulation-based learning. The technical considerations of the VR Lab setup and the animation software are proprietary to Zepth Pte Ltd.

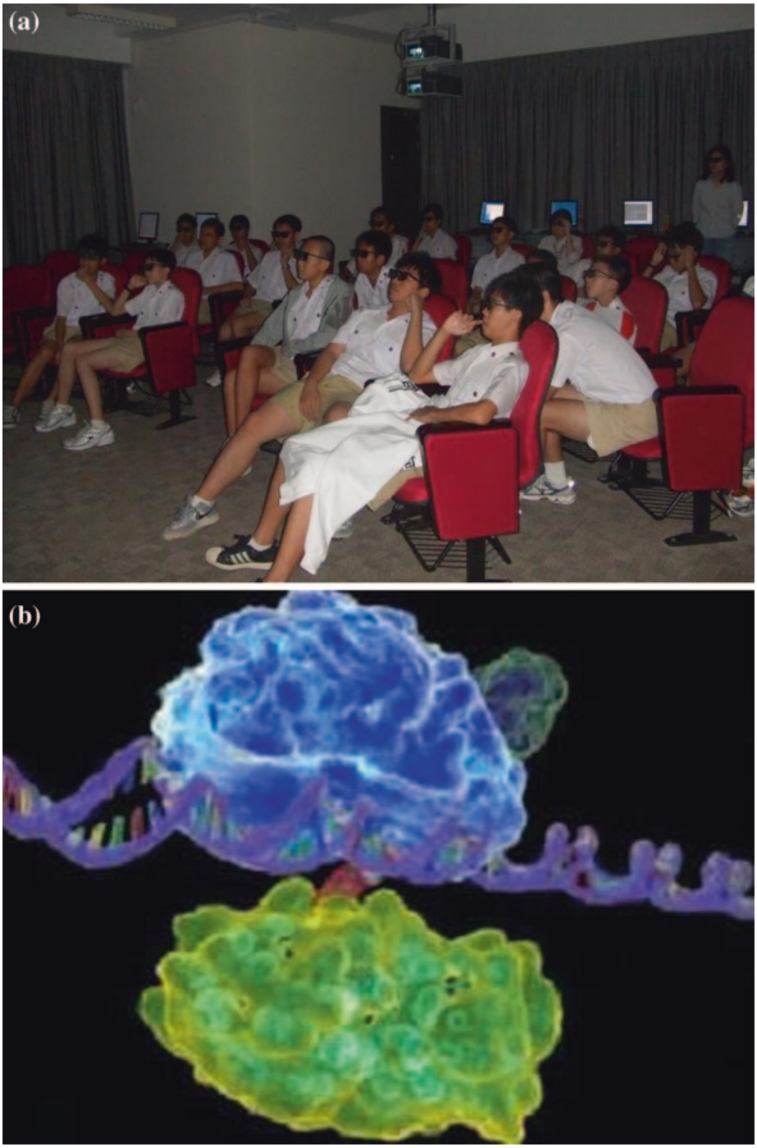

Fig. 2.1 **a** VR Lab @ HCI and **b** the 3D visualization of the protein transcription process in Molecular Biology

An example of a student handout is provided in Appendix I to illustrate how the visualization exercises were carried out.

Figure 2.1a shows the VR Lab @ HCI, and Fig. 2.1b shows the 3D visualization of the protein transcription process in Molecular Biology.

2.2.4 Implementation and Evaluation of Intervention

The proposed study involved Secondary 3 (Year 9) biology students from seven schools. These schools ranged from those admitting gifted and talented students to those whose students were average in ability. Purposive sampling was done so that participants had varying academic abilities but were fairly representative of Biology students in Singapore schools. Students in the experimental group were taught using the VR module to enhance visualization of Molecular Biology phenomenon, while students in the control group were taught the same content in the traditional way. Before and after the experiment, students in both groups did a survey on attitude and behavior toward Molecular Biology and a Molecular Biology achievement test.

In order to measure students' achievement in Molecular Biology, a questionnaire is specially formulated for the present study (Appendix II). It contains 10 two-step multiple choice items. The first part asks students about specific biological phenomenon, while the second part requires students to explain their answer based on key concepts. In this way, students who randomly "guess" the first answer will be found out in the second step. Each item is scored in two categories of either zero or one, depending whether participants demonstrate specific knowledge or core conceptual knowledge related to specific phenomenon; students who "guess" at the latter, but are unable to relate conceptual understanding with phenomenon are given zero scores. Such an approach increases precision when gaging students understanding.

Data were analyzed with the Rasch Unidimensional Measurement Model (RUMM 2030) computer program [2] using the Extended Logistic Model of Rasch [1]. Pretest items were scored in the same response categories to obtain a set of raw scores which were then allocated the equivalent Rasch linear measures from the posttest analysis. In this way, the pretest and posttest measures were fitted on the same linear scale, and thus can be validly compared. A two factorial analysis of covariance (two-way ANCOVA) allows determination of whether the main effects are independent of each other; that is, whether the two variables interact with each other. The two factors analyzed in the two-way ANCOVA are within-subjects factor (time), which is pretest versus posttest at two levels and between-subjects factor (treatment), which is teaching using the visualization exercises and software versus the traditional classroom method of "chalk and talk", also at two levels. A second two-way ANCOVA was also carried out to compare the pretest versus posttest scores of male and female students.

2.3 Results and Discussions

2.3.1 Summary of Rasch Analysis

Table 2.1 indicates that the item-person and person-item fit are good. The standardized fit residuals have a distribution with a mean near zero and a standard deviation

Table 2.1 Summary statistic, Person-item interaction

	Items		Persons	
	Location	Fit residual	Location	Fit residual
Mean	0.00	0.16	−0.31	−0.03
SD	0.95	1.05	1.14	0.63

near one, meaning that there is a good pattern of person and item responses consistent with a Rasch measurement model.

The Person separation index is an estimate of the true score variance among the participants and the estimated observed score variance using the estimates of their ability measures and the standard error of these measures [3]. The Person separation index is 0.73 and it is lower than the ideal of 0.9. It is an indicator that all the participant measures are not separated by more than their standard errors [3]. Based on this index, the achievement questionnaire can be improved by including some easy and difficult items to better target the high achieving participants.

Of the 20 items in the questionnaire, nine items measuring specific knowledge and nine items measuring conceptual understanding fit the measurement model with probabilities greater than 0.10 (except item 17). These are listed in Table 2.2, and their difficulties (locations) are presented, in order from easiest to hardest. Residuals represent the differences between the observed responses and the expected responses calculated from the Rasch measurement parameters. The residuals of each question fall within the standardized range of –2 to +2 (except item 1).

Item 15 is easiest whilst item 6 is reported to be most difficult. The items in the questionnaire that fit the Rasch model are a mix of both testing specific and conceptual knowledge in different topics of Molecular Biology. However, participants reported that the questions related to specific phenomenon (coded in green) were easier than questions probing conceptual understanding (coded in blue). This may be a reflection of current classroom pedagogy, and suggests that more needs to be done to help students in understanding and relating to “big ideas” and concepts in Molecular Biology.

2.3.2 Immersive VR Visualization Improved Achievement Scores

The measures for Molecular Biology achievement are displayed in graphical format separated by whether the intervention has been received (Fig. 2.2) and by gender (Fig. 2.3). These data are examined to determine the effects of the visualization exercises. The data are stratified according to gender and analyzed with ANOVA, showing $F(1, 245) = 7.54$, with $p = 0.006$. This means that males perform statistically significantly better than females in terms of achievement. Likewise, the mean experimental group measure is statistically significantly higher than the mean control group measure at posttest ($F(1, 245) = 7.54$, $p = 0.000$).

Table 2.2 Ordered difficulties for items in the molecular biology achievement questionnaire

Item	Location	Residual	Topic
15 (easiest)	−2.981	−0.499	Proteins and enzymes: digestion
7	−1.309	−0.089	Cell structure and function: organelles
1	−0.504	2.606	Cell structure: function-adaptation correlation
9	−0.420	−0.055	Cell structure and function: osmosis and diffusion
5	−0.250	1.591	Cell structure and function: organelles
11	−0.230	−0.699	Proteins and enzymes: nutrition
17	−0.226	1.859	Enzyme kinetics
13	0.099	1.126	Enzyme characteristics
19	0.181	−0.549	DNA: transcription, translation impacting cell function
8	0.287	0.392	Cell structure and function: organelles
4	0.335	0.306	Cell structure and function: transcription and translation
10	0.379	−0.236	Cell structure and function: osmosis and diffusion
2	0.463	−1.396	Cell structure: function-adaptation correlation
20	0.787	−0.285	DNA: transcription, translation impacting cell function
14	0.773	−1.113	Enzyme characteristics
12	0.858	−0.159	Proteins and enzymes: nutrition
18	0.872	−0.417	Enzymes kinetics
6 (hardest)	0.885	0.467	Cell structure and function: organelles

The items measuring specific knowledge are in green and the items measuring conceptual understanding are in blue

This indicated that the visualization exercises are effective in improving Molecular Biology achievement scores.

In order to ascertain that the results are not due to differential item functioning by gender, checks are carried out on whether the items work in the same way for male students as they do for female students. The item characteristic curves can be separated by gender and each item checked for differential item functioning. All items are found to show no statistically significant differential item functioning and an example is given for item 10 using ANOVA ($F(1, 7) = 0.12$, $p = 0.73$) in Fig. 2.4.

Tables 2.3, 2.4, and 2.5 give the two-way ANCOVA results of achievement scores and the interaction between the two independent variables, as indicated by "*", and their main effects displaying the sum of squares (Type III Sum of Squares), degree of freedom (*df*), *F* statistics (*F*), significance of the *F* statistics (sig.), and

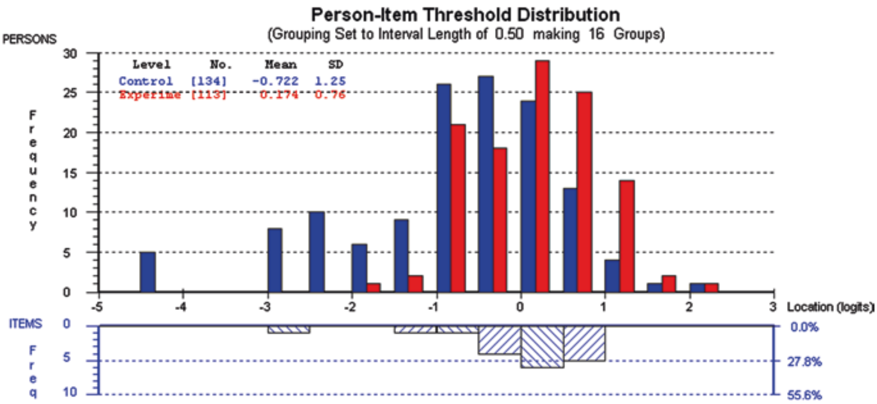

Fig. 2.2 Target graph by type for the Molecular Biology achievement questionnaire. For all Rasch measurements, the frequency of correct responses (*top*) is mapped against item difficulty (*bottom*)

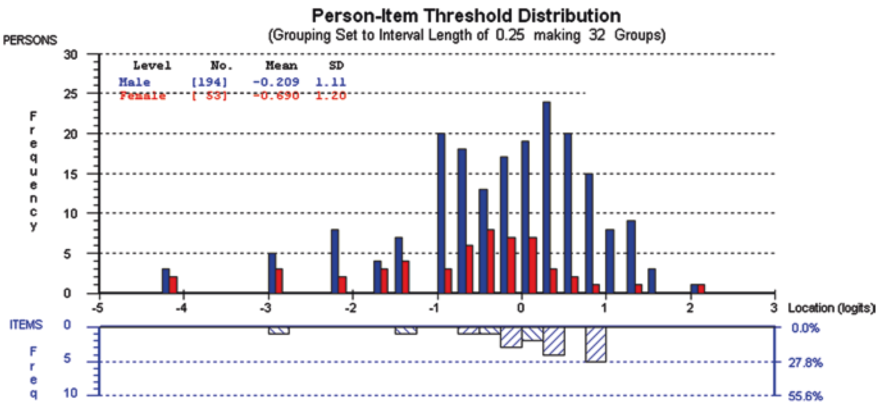

Fig. 2.3 Target graph by gender for the Molecular Biology achievement questionnaire

eta squared (Eta Squared) for each dependent variable. The eta squared is a measure of the effect size or magnitude of the effect. It describes the degree of association between the independent and dependent variable in terms of percentage. Figures 2.5, 2.6, and 2.7 shows changes in the mean measure of achievement at pretest and posttest in all participants, and in female and male participants, respectively.

Figure 2.5 show the differences in achievement scores between the control and experimental groups. There was a statistically significant difference in pretest and posttest achievement measures for the experimental group relative to the control group (Mean = –0.426 vs. –0.722) ($t = 1.937$, $df = 260$, $p = 0.02$). Additionally, the interaction effect reached statistical significance ($F = 3.54$, $df = 2$, $p = 0.03$). This means that the intervention effect of visualization in Molecular Biology resulted in significantly higher achievement measures for the experimental group overall.

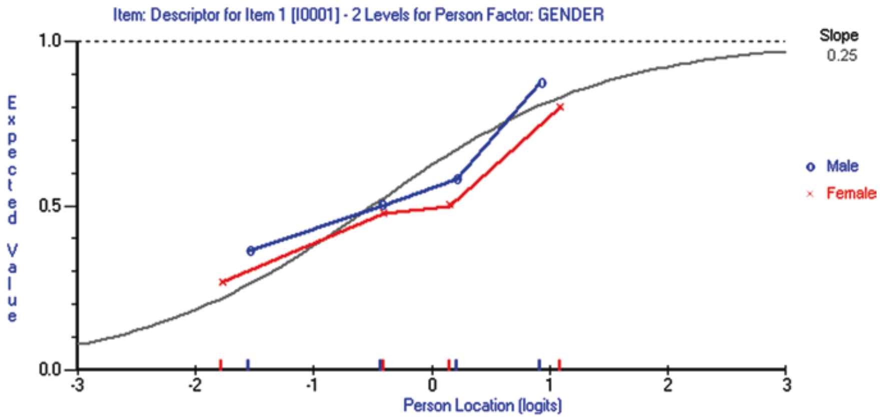

Fig. 2.4 Item characteristic curve with differential item functioning by gender for Molecular Biology achievement questionnaire item 10

Table 2.3 Two-way ANCOVA results of achievement measured in Logits in control and experimental groups

Source	Type III sum of squares	*df*	Mean square	*F*	Sig.	Eta squared
Corrected model	16.994[a]	2	8.50	12.99	0.00	1.03
Intercept	1.51	1	1.51	2.31	0.13	0.01
Group	0.03	1	0.13	0.15	0.83	0.00
Pre/Posttest	16.53	1	16.53	25.26	0.00	0.10
Group*Pre/Posttest	5.01	2	2.51	3.54	0.03	0.10
Error	148.49	227	0.65			
Total	167.10	230				
Corrected total	165.48	229				

[a] $R^2 = 0.103$ (Adjusted $R^2 = 0.95$)

Examination of pretest and posttest differences in achievement between genders yielded mixed results. Figure 2.6 indicates difference between female participants in the experimental and control groups, but the interaction effect did not reach statistical significance ($F = 0.10$, $df = 2$, $p = 0.90$). Similarly, Fig 2.7 shows that male participants in the experimental group maintained higher achievement measures than the control group, but this was due to the invention and the interaction effect which was statistically significant ($F = 4.93$, $df = 2$, $p = 0.01$). Therefore, while the interaction effects are not statistically significant in the case of female participants, the intervention for visualization in Molecular Biology produces improvement in male participants and overall in the study.

Table 2.4 Two-way ANCOVA results of achievement measured in Logits in female control and experimental groups

Source	Type III sum of squares	*df*	Mean square	*F*	Sig.	Eta squared
Corrected model	2.695[a]	2	1.35	1.97	0.15	0.09
Intercept	0.14	1	0.14	0.20	0.66	0.00
Group	0.04	1	0.91	0.55	0.82	0.00
Pre/Posttest	2.57	1	2.57	3.76	0.06	0.09
Group*Pre/Posttest	0.15	2	0.07	0.10	0.91	0.00
Error	25.99	38	0.68			
Total	28.82	41				
Corrected total	28.69	40				

[a] $R^2 = 0.094$ (Adjusted $R^2 = -0.046$)

Table 2.5 Two-way ANCOVA results of achievement measured in Logits in male control and experimental groups

Source	Type III sum of squares	*df*	Mean square	*F*	Sig.	Eta squared
Corrected model	13.26[a]	2	6.63	10.68	0.00	0.12
Intercept	0.01	1	0.01	0.03	0.87	0.00
Group	2.90	1	2.90	4.67	0.03	0.03
Pre/Posttest	2.57	1	2.57	3.76	0.06	0.09
Group*Pre/Posttest	11.04	2	11.04	17.78	0.00	0.01
Error	101.27	163	0.62			
Total	114.87	166				
Corrected total	114.53	165				

[a] $R^2 = 0.116$ (Adjusted $R^2 = 0.105$)

2.3.3 *Immersive VR Visualization Increased Engagement, Interest, and Understanding*

To better understand the improvements in scores, 26 male students were gathered for focused group interviews. The participants were asked about their perceptions of Molecular Biology before and after experiencing the visualization exercises. Four main themes were elucidated from the responses.

Theme 1: Prior to the study/exposure to VR elements, students found Molecular Biology difficult to understand and were intimidated by the subject.

There was almost unanimous agreement among students that Molecular Biology was difficult to grasp. These students noted their fear and anxiousness when first exposed to the subject. While their nervousness generally subsided over time, their difficulties in understanding the topics remained. Typical student comments were:

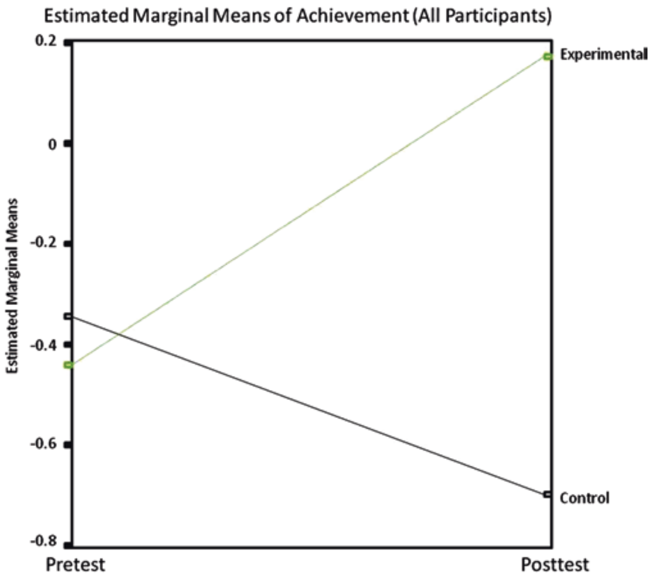

Fig. 2.5 Graph of estimated biology achievement mean scores in Logits against pretest versus posttest for experimental and control group participants

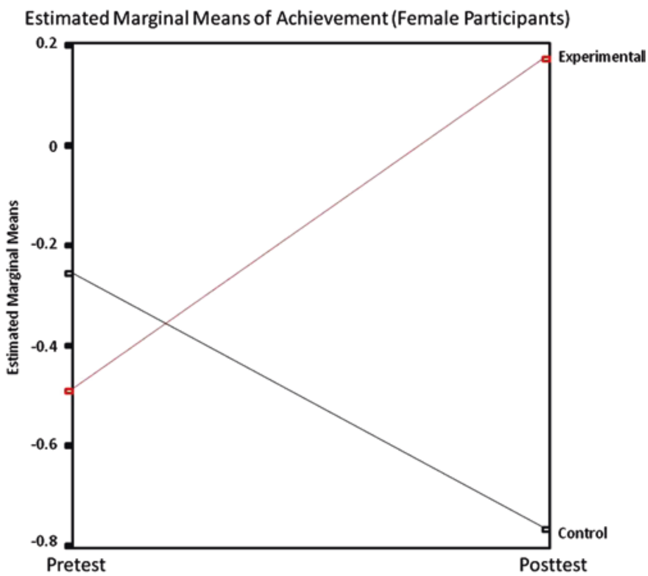

Fig. 2.6 Graph of estimated biology achievement mean scores in Logits against pretest versus posttest for female experimental and control group participants

The topic of Molecular Biology was a daunting one which was extremely hard to understand clearly, due to the complexity of the organelles and the interactions between them.

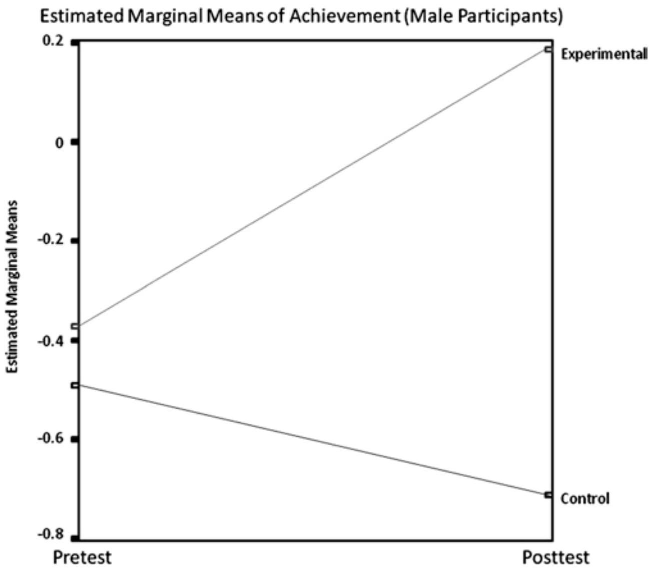

Fig. 2.7 Graph of estimated biology achievement mean scores in Logits against pretest versus posttest for Male experimental and control group participants

> Initially, Molecular Biology had been an exceptionally intimidating topic to me. We are often presented with static images that provided us with a limited understanding of how various organelles within a cell operates and looks like. Furthermore, dozens of organelles are revealed at once, without any former introduction of any sort, resulting in a rigorous experience for students to grasp after a single lecture.

This fear and lack of understanding even led students to give up the subject altogether in Junior College.

> I thought that Molecular Biology was dry and complicated. I did not wish to study Molecular Biology in a more in-depth manner as it was far too complicated.
> I thought that Molecular Biology was especially confusing and disturbingly hard to understand. Especially because this topic would become more in depth in Junior College, I decided to drop biology and instead continue with the other 2 Sciences, Physics and Chemistry.

Theme 2: Prior to the study/exposure to visualization exercises, students found Molecular Biology abstract.

The most important reason cited for a lack of understanding was the degree of abstraction found in topics in Molecular Biology. The inability to see, hear, and touch phenomenon at the molecular level contributed difficulty in comprehension. Several students went further to cite the disjuncture between what images presented and verbal explanation in class as a major contributor to their confusion. One student admitted that he had to rely on “imagination” to help him guess the phenomenon. Students described their lack of understanding in the following comments:

> Molecular Biology seemed to be an abstract idea… I could not really grasp. Even though clear pictures were used in PowerPoints to illustrate various concepts, it was hard to clearly figure out the interactions between various entities such as the cell organelles.
> Molecular Biology is a topic which students do not come into contact with often in life, thus it is an abstract topic.
> Molecular Biology is an abstract topic that is hard to grasp, thus making it a little boring. The Powerpoint slides and available pictures also didn't really help me understand it fully, thus studying it for exams was rather tedious as I didn't really understand fully what I was studying.
> It was difficult to conceptualize at times. As a result, one had to rely on one's own imagination to learn, ending up where some might learn it wrongly.

Theme 3: Prior to the study/exposure to visualization exercises, students relied on rote memorization to cope with Molecular Biology.

To help themselves do well, in spite of their lack of understanding, students relied heavily on rote memorization as means to score in tests. Almost all students believed that memorization was necessary; even students of higher ability regarded it as the most effective way to do well.

> The content of Molecular Biology lessons involved a lot of memorization work. Furthermore there were numerous terms which had to be learnt, which made things even more complicated.
> Studying Molecular Biology heavily relies on a student's memorization skills.
> The fact that we were only taught via pictures did not help but only made me memorize the steps that happened in things like transcription and translation without any understanding so that I would get high marks when answering test and examination questions.
> I had some decent understanding of Molecular, but I never tried to visualize it so it was mostly just memorizing terms and the way it works.

The role of memorization was deemed as crucial, superseding understanding, and even in very able students. This finding points to an area of concern for curriculum managers and a need to re-examine pedagogy in schools. While traditional achievement tests indicate that schools in Singapore are generally doing well in (MOE 2008), students' comments indicate that tests need to be more closely scrutinized for questions that stress application of concepts and that more resources need to be developed to help student conceptually in the Molecular Biology.

Theme 4: Students agreed that visualization was crucial to understanding Molecular Biology.

Prior to the visualization exercises, students indicated a cognitive gap between what was explained and what was shown to them in class.

> These perceptions were a result of a lack of resources in thoroughly explaining the concepts to the students. Visually, I was very lost, and could not imagine what it was like at a molecular level.
> Molecular Biology was a fairly interesting topic, however I found the topic hard to understand from the perspective of a visual learner such as myself, where diagrams alone could not accurately depict the processes. Molecular Biology occurs on a minute scale, and hence the methods of depiction used are either inaccurate or static, which may hamper our capability to comprehend the topics taught.
> Powerpoint slides featuring various pictures of molecular related stuff was not sufficient for me to fully comprehend the complexity of Molecular Biology, leading to many

> misconceptions. Many of the Powerpoint slides are also presented in text, forcing me to speculate images (of molecules), which was fairly tough at times, and this leads to my slow progress on topics that touch on Molecular Biology.

After viewing the animations and participating in the visualization exercises, student cited increased interest and engagement in the subject. Increased focus also resulted in better understanding about concepts learnt previously in class.

> The most enjoyable about the visualization exercises were the dynamic 3D molecular structures that kept me captivated. Static images that I used to study with in the past had little or no appeal at all.
>
> I enjoyed the interesting and unique method of presenting the idea of Molecular Biology.
>
> I liked the fact that the visualization exercises made it very interesting and exciting to students like me. We not only understand the topic better, but the visualization exercises helped me look forward to learning more, because learning has been made easier in this field and even more interesting.
>
> The close-up of Molecular Biology through 3D visualization exercises was most useful as they provided me with a clearer understanding of molecular structures.
>
> The visualization exercises were most useful in that the animations allowed me to better grasp the processes taught step-by-step, as compared to static visuals or 2D animations by viewing the processes from a new perspective. For instance, on the flu virus life cycle, one can better visualize the entry of virus DNA/RNA into the cell and specifically how they replicate via the creation of cell DNA/RNA in the cell nucleus, as well as the proteins formed on the cell membrane. This helped me to grasp various aspects of Molecular Biology, especially processes such as transcription and translation, as these occur on minute scales, and the topics can be difficult to grasp without the aid of animations.

The improved cognition of Molecular Biology processes resulted in greater interest and engagement. This was important in generating better learning attitudes and behaviors, which in turn translated to greater achievement in male students.

2.4 Conclusion

The data for the Molecular Biology Achievement Questionnaire are analyzed with the Rasch Unidimensional Model (RUMM2030) computer program [2]. The results show that the item-person and person-item fit were good. The Person separation index, measured 0.73, indicates reasonable reliability and consistency of the measures along the scale of achievement.

The visualization exercises are effective in improving Molecular Biology achievement scores; students in the experimental group perform statistically significant better than the control group students in achievement at posttest. And while there is statistically no significant differential item functioning by gender, male participants perform statistically significantly better than females in achievement at posttest.

Items testing specific knowledge were easier than the items testing conceptual understanding, indicating that students found it hard to translate their awareness of phenomenon into corresponding general concepts. This is a potential area of improvement for teaching and learning Molecular Biology in the Singapore context in which academic program managers should look into.

Interviews with students indicate that the visualization exercises helped to increase understanding whilst stimulating interest and engagement. All these serve to bring about significant improvements in achievement scores. Prior to these exercises, students relied heavily on rote memorization to do well in tests. The possibility of achievement without deep learning is an area of concern for all teachers and worth examination by administrators in their own schools.

Overall, the visualization exercises conceptualized, initiated, and evaluated indicate that these are useful to promote understanding of achievement in Molecular Biology. It is hoped that the resultant developmental framework and lesson plans may serve as a guide to teachers looking to improve teaching and learning Molecular Biology in secondary schools in Singapore, as well as other aspects of teaching and learning that are heavily dependent on visual elements.

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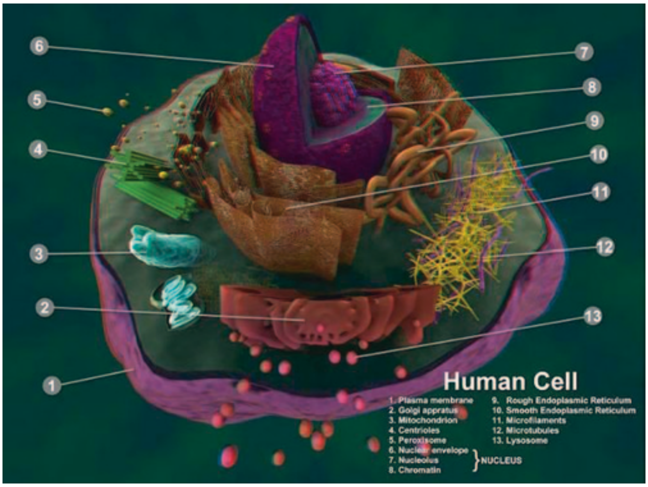
Appendix I: Sample Student Handout for Visualization Exercise

Cell Organelles, Functions, and Interactions



In this exercise, you will "look at" the various structures of a human cell to gain a better understanding of its function. You will also compare and contrast the plant and animal cells.

Get together in your groups after each segment to answer the questions below.

Your group should also sketch your ideas and questions on the blank sketch pad on the walls and use the plasticine provided to build and refine your cell models.

Cell Membrane

1. What are the components of the cell membrane?
2. Why are the different components arranged this way? What interactions enable them to stay in place?

Nucleus

1. What is the function of the nucleus?
2. How is the nuclear membrane different from the cell membrane?

Endoplasmic Reticulum

1. What is the function of the endoplasmic reticulum?
2. What are the differences between the smooth and rough endoplasmic reticulum?
3. How are the nuclear membrane and the endoplasmic reticulum connected?

Golgi Body

1. What is the function of the Golgi body?
2. There is a polarity to the Golgi. What are the differences between the "cis" and "trans" faces of Golgi?
3. How is the Golgi membrane connected to the cell membrane?

Plant Cell versus Animal Cell

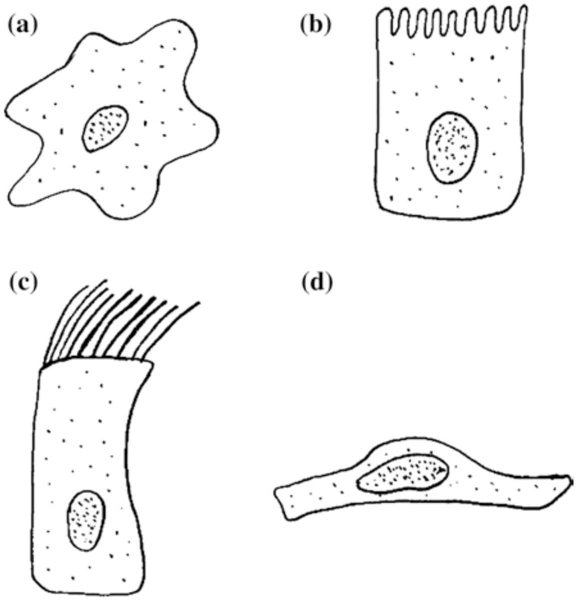
1. What are the differences between a plant and an animal cell?
2. What properties does the cellulose cell wall confer on a plant cell?
3. How is the central vacuole different from the vacuoles of an animal cell?

Appendix II: Biology Achievement Questionnaire

Each multiple choice question is divided into two parts.

The first part asks a specific question related to Molecular Biology.
The second part asks for an explanation of the answer given in the first part.
In each case, choose the most appropriate answer from the options given.
You will score 1 mark if you get the first part of the question correct.
You will score 2 marks if you get both parts of the question correct.
You will not score any marks if you get the second part correct but the first part wrong.

1. Which of the following cells is adapted to absorb nutrients efficiently?



Explanation:

A increased surface area increases rate of active transport
B increased surface area to volume ratio increases rate of active transport
C increased surface area increases rate of diffusion
D increased surface area to volume ratio increases rate of diffusion

2. Radioactive amino acids were introduced into the cytoplasm of human pancreatic cells that were actively synthesizing protein. The cells were maintained for 3 days in a culture medium.

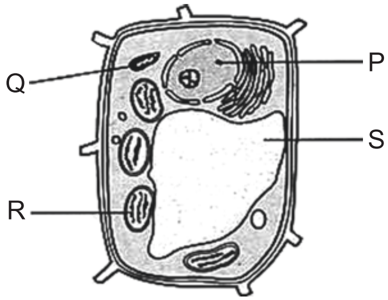
In which of the following would radioactivity not be detected?

A nucleus
B endoplasmic reticulum
C Golgi body
D ribosomes

Explanation:

A the nucleus controls the activity of a cell
B the endoplasmic reticulum is involved in protein synthesis
C the endomembrane system allows organelles to share lipids
D the Golgi body packages proteins

3. The figure below shows the organelles in a plant cell. Which of the following statements about the labeled parts is incorrect?



A P controls the activities in the cell
B Q is the site of aerobic respiration
C R is the site of synthesis of energy
D S stores food

Explanation:

A the nucleus controls the activity of a cell
B the mitochondria oxidize glucose to produce ATP
C the chloroplasts reduce carbon dioxide to produce glucose
D the vacuole stores metabolic waste

4. An amoeba had its nucleus removed. For several days it continued to move and feed, but it did not reproduce. An intact amoeba reproduced twice in that time. What conclusions do you draw from this experiment about the role of the nucleus in the amoeba?

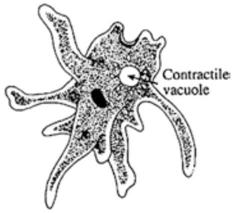
A The nucleus is necessary for cell division
B The nucleus regulates the activity of the cell

C The nucleus is the only part of the cell that contained DNA
D The nucleus is necessary for the cell to grow

Explanation:

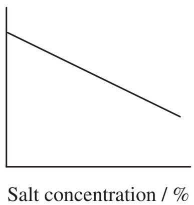
A DNA is necessary for reproduction
B DNA is necessary for growth
C DNA is necessary for movement
D DNA is necessary for feeding

5. *Amoeba proteus* is a small aquatic organism which lives in freshwater ponds. It has a contractile vacuole which slowly increases in size, and then suddenly contracts and vanishes when the liquid within it is being forced out of the amoeba into the surrounding water. This helps in the removal of excess water from the amoeba. Soon, the vacuole reappears and again slowly increases in size, and the process is repeated.

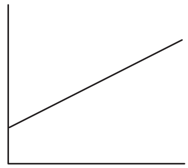


Which of the following graphs show a correct relationship between the frequency at which the vacuole is emptied and the concentration of salt in the surrounding water?

A Frequency of contraction/min^{-1}



B Frequency of contraction/min^{-1}

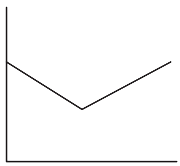


Salt concentration / %

C Frequency of contraction/min^{-1}

Salt concentration / %

D Frequency of contraction/min^{-1}

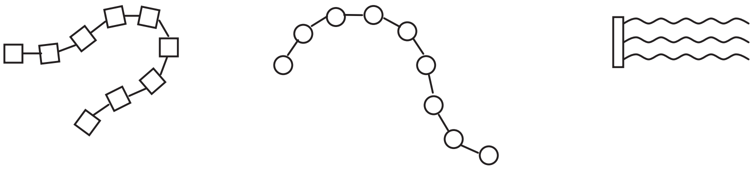


Salt concentration / %

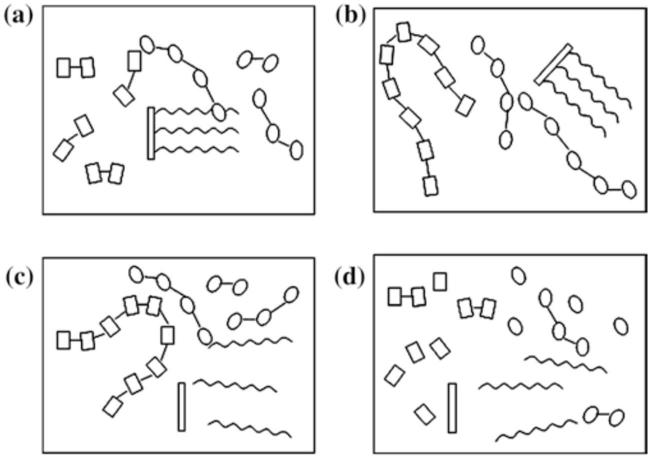
Explanation

A water moves down a concentration gradient
B water moves down a potential gradient
C water moves against a concentration gradient
D water moves against a potential gradient

6. The diagrams below represent molecules of starch, protein, and fat.



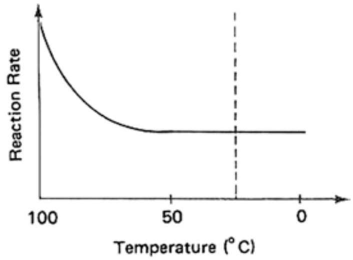
Which of the following mixture of molecules will be found in the stomach?

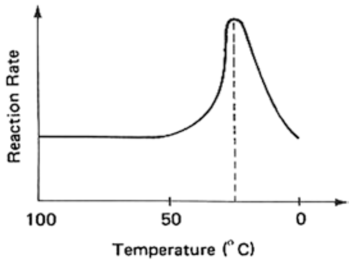


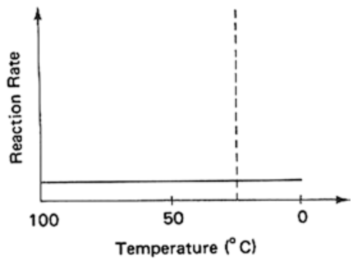
Explanation:

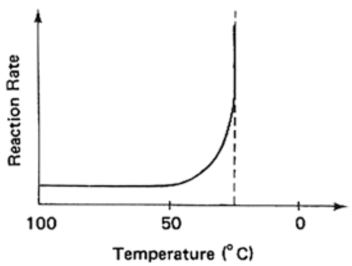
A starch is digested in the mouth
B protein is digested in the stomach
C fats are digested in the mouth
D fats are digested in the stomach

7 Which of the following graphs show the rate of reaction when a hot mixture of proteins and pepsins are cooled down from 100 to 0 °C?


Reaction Rate
100
50
0
Temperature (°C)


Reaction Rate
100
50
0
Temperature (°C)

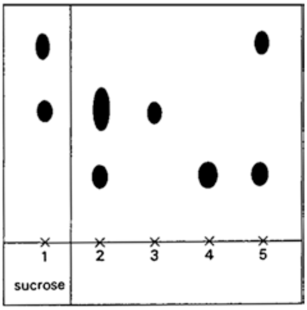

Reaction Rate
100
50
0
Temperature (°C)


Reaction Rate
100
50
0
Temperature (°C)

Explanation:

A inactivation is reversible
B denaturation is reversible
C inactivation is irreversible
D denaturation is irreversible

8 Five disaccharides were hydrolyzed with dilute acid, and the purified products were separated by 1D chromatography. The final chromatogram is shown in the diagram.



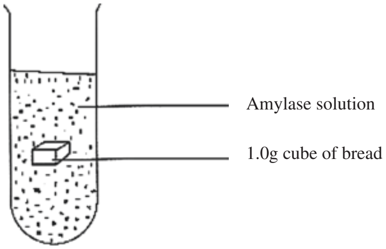
If spot 1 represents the products obtained from the hydrolysis of sucrose, which one of the following indicates the results obtained from the hydrolysis of lactose and maltose?

	Lactose	Maltose
A	2	3
B	2	4
C	5	2
D	5	3

Explanation:

A both lactose and maltose are diasaccharides
B maltose is made up of glucose
C lactose is digested by lactase
D maltose is digested by maltase

9 The figure below shows an experiment to investigate the action of amylase on a 1.0 g cube of bread. After 20 min at 25 °C, 0.4 g of bread was digested.



If the experiment was repeated at a temperature of 35 °C, which of the following would be obtained?

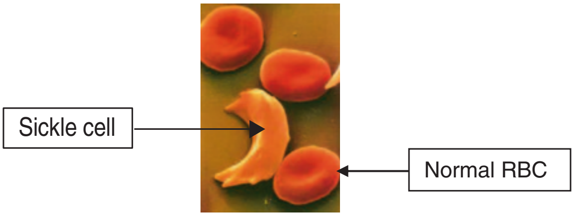
A 0.2 g of starch
B 0.8 g of starch
C 0.2 g of maltose
D 0.8 g of maltose

Explanation:

A enzyme activity is dependent on temperature
B enzyme activity is dependent on pH
C enzyme activity is dependent on substrate concentration
D enzyme activity is dependent on enzyme concentration

10 Sickle cell anemia is a defect due to a mutation of the hemoglobin gene. People with such condition often suffer from breathlessness. The mutation leads to the production of a wrong type of polypeptide chain which makes up hemoglobin. In the abnormal polypeptide chain, the sixth amino acid is replaced by valine.

The result of such mutant is that the shape of the red blood cells is changed.



Explain how this change would affect the ability of the red blood cell to serve its function.

A less oxygen is transported
B less nutrients are transported
C more carbon dioxide is transported
D more metabolic waste is transported

Explanation:

A the change in one amino acid residue changes the primary structure
B the change in one amino acid residue changes the secondary structure
C the change in one amino acid residue changes the tertiary structure
D the change in one amino acid residue changes the cell structure

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