Descriptive Account

Photosynthesis *In Silico*. Overcoming the Challenges of Photosynthesis Education Using a Multimedia CD-ROM

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Abstract

Photosynthesis is a central topic in biology education. It remains one of the most challenging, largely because of a) its conceptual difficulty, leading to lack of interest and misconceptions among students; b) the difficulties students have in visualising the process, or relating it to things they can see, especially when the topic is presented purely as a molecular process; and c) limitations to the practical demonstration of photosynthesis because equipment is either cheap, unreliable and antiquated or prohibitively expensive.

In response, we have combined expertise in photosynthesis research and education, and in graphic design, to produce an interactive, multimedia package, available on CD-ROM, containing two practical modules and three theoretical modules, for tertiary level students. Features include an animation of photosynthetic electron transport, suitable for a lecture presentation or for self-paced learning by students, and experimental simulations of photosynthetic gas exchange and chlorophyll fluorescence which can be used either as stand-alone packages or, where equipment is available, to supplement and enrich a laboratory demonstration/experiment. As well as improving learning outcomes through the documented advantages of computer-based learning, this set of modules provides students with access to the latest experimental techniques and theory, improving their understanding, updating their skills and switching them on to the amazing process that brings energy into our biosphere.

Keywords: biology education, experimental simulations, interactive multimedia, chlorophyll fluorescence, electron transport chain animation, photosynthetic oxygen evolution

Background - The challenges of photosynthesis education

Photosynthesis raises a number of challenges for students and teachers. Plant science is, in general, under-represented in high school and undergraduate courses (Hershey, 1991), and often receives a poor response, especially from students enrolled in biomedical type courses (“if it doesn't bleed, it isn't interesting”; Hershey, 1992). Aware of the central role of this process in biology, teachers struggle, nevertheless, to promote the relevance and importance of photosynthesis to their students. The challenges they face are associated with the conceptual difficulty of the topic, the microscopic and abstract nature of the process, making it difficult to picture, and technical difficulties with demonstrating photosynthesis experimentally. These will be discussed in this section.

Conceptual difficulty

Photosynthesis is a topic that spans disciplines (biophysics, biochemistry, ecophysiology) and organisational levels (molecules, cells, organs, organisms, ecosystems). The unique, complex and fundamental process of photosynthesis draws the dedicated research interest of thousands of researchers in multiple disciplines from around the world (the International Society of Photosynthesis Research lists 2800 researchers in its directory). Yet, photosynthesis is often de-emphasised in Biology curricula, because of the tendency to focus on animals, but also because of the conceptual challenges of understanding this multi-faceted process. More than most topics in biology, major misconceptions often persist in students' understanding of photosynthesis (Haslam & Treagust, 1987; Lonergan, 2000; Ebert-May *et al*., 2003). These include belief that:

- Plants get most of their food from the soil (which is why they need fertiliser).
- Photosynthesis is the simple conversion of CO_2 and water to carbohydrates and O_2.
- Plants photosynthesise during the day and respire at night.
- Chlorophyll molecules in the light harvesting complexes transfer excited electrons to the reaction centre.
- Plants are green because they absorb green light.

In addition to these major misconceptions, students may become familiar with words and descriptions of processes such as electron transport, light harvesting, oxygen evolution and carbon fixation, but may have only very shallow, and in some cases flawed, understandings of what these processes really are. Although they may be able to develop these concepts sufficiently to pass exams in their first couple of years (Edmund, 1986), their 'literacy' in this area is likely to remain at a low level (Uno & Bybee, 1994), and they may have to 'unlearn' and relearn this material at higher levels as flaws in their understanding begin to compromise their progress in this area.

Visualising Photosynthesis

Biology education can be much enriched by the use of images (Beakes, 2003). This is particularly the case with modern uses of multimedia and the web, but is made possible by the visual nature of biology and its subjects, the living world presenting a veritable feast to the eyes. For this reason, biology may attract students (and teachers) who are visually oriented and learn best when presented with images, and worst when presented with abstract concepts. This may explain some of the difficulties with understanding abstract processes that cannot, in general, be seen, like photosynthesis. Even parallel processes in animals, such as respiration, can at least be related to observed or experienced processes such as breathing, digestion and the use of metabolic energy in movement, etc. Plants, apart from very slow growth, appear to do nothing at all.

One of the common approaches to the teaching of photosynthesis that may exacerbate these problems is the 'bottom up' approach of treating photosynthesis as purely a molecular process. Photosynthesis can be described within a full range of spatial scales, from a forest down to a chloroplast. Contextualising the process as it occurs at the more visual, familiar level of a leaf or plant (eg Weyers *et al.*, 1998) can make the whole topic more accessible to students and give them a framework to move on to molecular details.

In addition to providing this broader context, and making use of the students own visual capacities and experiences, there is also a need to present the abstract, molecular level processes in a visual way (Trindade *et al.*, 2002). This is normally done through the use of models and graphics. However, in interpreting what is known about photosynthesis into visual pictures that can be grasped by students, there is a danger that misunderstandings and misconceptions are reinforced or created (Storey, 1989). This is particularly the case for introductory texts, which tend to use simplified graphics produced by graphic experts, rather than scientific experts. Given that many biology teachers are also non-experts in the area of photosynthesis, a low level of understanding of the process tends to persist.

Practical aspects of photosynthesis

There are significant problems with teaching the practical aspects of photosynthesis. Laboratory exercises are available, but revolve around equipment and procedures that are either cheap and unreliable or prohibitively expensive, particularly for large classes. There are some very elegant experiments demonstrating the principles of, for example, gas exchange (e.g. the classic *Elodea* experiment (see below); Buttner, 2000; Fox, *et a*l., 1999), but they are often quite slow and require precision to gain meaningful results. Significantly, if students are unclear about the principles before the practical, and take insufficient care in collecting the data, they may gather data that is inconsistent with theoretical expectation. Rather than clarifying concepts, this will merely reinforce misconceptions or generate confusion (or both). In large practical classes in particular, learning outcomes are affected by the quality of demonstration and the success of a particular experiment. This can result in variability within and between practical classes in any cohort, which has implications for equity, and well as for learning outcomes generally. An ideal approach would be to use such experiments as demonstrations, either in the practical class or lecture, so that students can see with their own eyes that the process is real, macroscopic and visual, but to also provide a more reliable practical experiment for the students to participate in.

We would like to suggest that there is another problem with many of the available practical demonstrations and experiments for teaching photosynthesis. Such experiments often have a long history, and many classic early experiments are recovered from antiquity to demonstrate principles to University students. Unless these are presented in their historical context (Hershey,1991), the use of antiquated equipment and techniques in University courses, while they may be educationally sound and consistent with resource constraints, create a false picture of modern science. As well as creating a picture of plant research as out-of-date and old-fashioned, they create a romantic impression of experimental science in terms of simple measurements, direct observations, simple, home-made equipment, ingenuity and trouble-shooting. While the skills and knowledge students pick up from these may be valuable in themselves, and such activities ought not to be dispensed with completely, they are out of step with modern, high tech, big science, with its sophisticated and expensive instrumentation, automation and black box data collection. Practicals based entirely on antiquated experiments do not prepare students for work in modern science, or even for an appreciation of modern science and its methods. They may also act to further devalue plant sciences as 'old science' in the student's eye.

A response to these challenges

In the context of these challenges, there is clearly a need for new materials and approaches to teaching photosynthesis. These need to present photosynthesis in all its complexity, but in a way that stimulates the interest and excitement of students, and promotes deep and accurate understanding. We have produced an interactive multimedia package that draws on our extensive knowledge as researchers and teachers in the photosynthesis area (Robinson & Russell) and on skills in graphic and computer design (Netherwood). Multimedia has the potential to bring abstract concepts and invisible objects and processes to life, and to do so in a flexible and reliable way which increases retention and learning (Moore & Miller, 1996). The interactive, user-friendly format and excellent graphics should improve students' satisfaction and attention, and their learning outcomes (Evans, *et al*., In press). In combining written and spoken word with dynamic pictures, models and animations, the resource should suit a range of students and learning styles, including the visually oriented (Beakes, 2003).

The multimedia package, available on CD-ROM, is designed as a series of modules (currently five, see Table 1) for flexible use. The modules are designed to supplement and enrich courses rather than as an alternative and may be used in a blended learning mode to augment lectures, tutorials and practical classes and by students as individuals or in groups for self-paced learning. The range of modules and the depth of material in the modules, together with the easily-navigable format and internal choices, mean that the multimedia package is also flexible in terms of the audience, and can be used from senior high school/1st year University to postgraduate level. The modules are all interactive, providing flexibility to students in the pace, depth, and sequence in which they complete material in the modules, in or out of class time. All modules include an extensive, up-to-date list of references. Details of the modules and selected examples are presented below.

Table 1. The five modules of the 'Photosynthesis in silico' CD-ROM, showing topics and target audience. The target audiences are given as years where these modules are currently in use at the University of Wollongong.

Module #	Topic	Target audience
1	Oxygen evolution by *Egeria* a) Effect of light quality on photosynthesis b) Effect of light quantity on photosynthesis in sun and shade leaves	1st Year 2nd Year
2	Plant adaptations to sun and shade	2nd Year
3	The photosynthetic electron transport chain	2nd Year
4	How do plants cope with excess light?	3rd Year
5	Measuring photosynthesis using chlorophyll fluorescence	3rd Year

Practical modules

Modules 1 and 5 are experimental simulations, one based on the classic Elodea (now Egeria) gas exchange experiment, and the second involving the use of chlorophyll fluorescence, one of the most important experimental tools in modern photosynthesis research. The simulations offer many of the benefits identified by Miller and Hamilton (1992, p 13), including allowing students to explore experimental conditions (such as light quantity and quality), replacing expensive or unreliable practical exercises and developing higher order cognitive skills. They offer the students a very similar range of tasks and cognitive exercises as the hands-on practical equivalents and allow the streamlining of data collection and analysis. They also ensure that a consistent practical outcome is achievable by all students, even in large classes, and that theoretical aspects are not obscured because of technical problems. The great advantage of these experimental modules is that the practical outcome is determined by the programmers and although we have incorporated variation, as befits biological experimentation, it is not so great as to obscure the message.

The first simulation in **Module 1** was designed to replace a first year practical within a Biochemistry and Cell Biology course where students study the effects of light of different wavelengths on photosynthesis in the aquatic plant *Egeria*. In previous years this practical had yielded extremely unreliable results, often the opposite to that expected. Although anomalous results and artifacts are common when using biological systems, they are a poor introduction to the complex process of photosynthesis. Obtaining more reliable practical results would have necessitated the purchase of 20 sets of expensive glass filters and provision of a light meter. With practical classes of 80 students (400 total enrollment) this was not practical. However, the experiment is a very elegant demonstration of a key concept in photosynthesis, particularly in demonstrating that the apparently molecular process of gas exchange can be visualised at the whole leaf level. The solution has been the production of a simulation to replace this practical. A screen shot from this module is shown in Fig. 1.

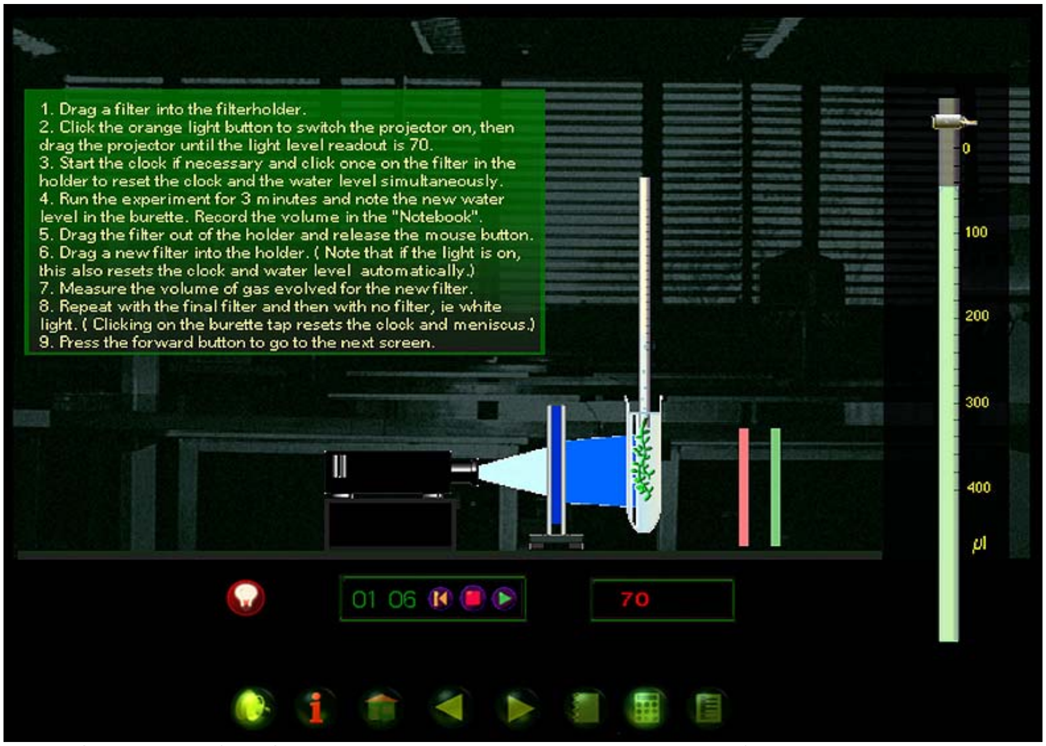

Fig. 1. *Screen shot of the O_2 evolution by Egeria experimental simulation from Module 1a.*

The second simulation in this module is an investigation of the effect of light quantity on the rate of O_2 evolution. Students can use plants collected from the surface of the pond (sun plants) or from deeper water (shade plants). By altering the amount of light incident on the plants, the students can investigate the light levels at which the photosynthetic rate is saturated and are introduced to the concept of light response curves. Since variation is built into the results students working in groups can produce a set of "replicated" data from which they can calculate means and standard deviations. Module 2 (see below) contains complementary material for this second simulation allowing students to understand the theoretical aspects of plant adaptation to various light levels. The two modules together can thus be used as the basis for a written report within which students explore the practical and theoretical aspects of photosynthetic responses of plants to changes in light environment.

Chlorophyll fluorescence, the basis of the simulation in **Module 5**, is probably the most widely used tool in photosynthesis research in the world today (Schreiber *et al*., 2000). This technique is generally out of the reach of undergraduate students because of the expense of equipment and the complexity of the theoretical background to this technique. This is unfortunate given that chlorophyll fluorometers are easy to operate and represent a quick, direct and reliable method for photosynthesis measurement. The production of less expensive teaching fluorometers will hopefully improve their uptake into the teaching arena. A major aim of the PHiS project was to allow senior students to meaningfully interact with experimental simulations to facilitate understanding of equipment used in project work and in the wider world of scientific research. Module 5 is used to supplement a third year plant ecophysiology practical class where the students are introduced to techniques that they will use in a project later in the course. The module explains the theoretical basis underlying the use of chlorophyll fluorescence and also provides two experimental simulations where the students determine the effect of increasing light levels on photosynthetic electron transport rate or the induction of photosynthesis in a leaf. This module is also very useful as an introduction to chlorophyll fluorescence for students entering Honours, Masters or PhD research projects.

Theoretical modules

Modules 2 - 4 (Table 1) cover theory in areas at the forefront of research which are not currently well described in the available texts, are conceptually difficult for students and/or are better illustrated through animation. The computer-based delivery allows these exciting areas of plant biology to be brought to life in a way that textbooks cannot achieve. Modules 2 and 4 contain many of the features recommended for Virtual Lectures by Evans *et al*. (In press), including material structured to different levels, and navigational choice and information, but also introduce a feature whereby dynamic figures are matched to scrolling text. This allows figures to build, as in a PowerPoint lecture presentation, in line with ideas that are introduced in the text as the students scroll through at their own pace. Combined with animations, figures and photographs, the dynamic, interactive format makes the modules visually stimulating and clarifies and reinforces concepts. In particular, these modules encourage students to move from the plant and leaf level to the molecular level and back, enhancing the relevance and accessibility of photosynthesis to them and improving their understanding (a similar approach is used in experimental studies developed by Weyers *et al*., 1998).

These modules complement the practical modules and are thereby mutually reinforcing. Module 2 (Plant Adaptations to Sun and Shade) complements the light quantity investigations of the first practical module (Module 1) and Module 4, which covers the response plants to excess light stress, contains theoretical material to complement the fluorescence module. These theoretical modules, by presenting up-to-date information from the research literature, also form a bridge between textbooks and the scientific literature that will hopefully facilitate the students' ability to access the primary literature.

Module 3, the photosynthetic electron transport animation, is a highlight of the package, and responds to one of the fundamental challenges of teaching in areas such as biochemistry and biophysics - the comprehension of objects and processes that can not be seen or experienced. As scientists, we learn about things like proteins, membranes, electron transport and light harvesting from indirect observations, using measuring systems and analytical methodologies of various sorts. Knowledge about the nature of these invisible entities evolves, punctuated by controversy and consensus about the actual structures and the characteristics which define them. Regardless of the sophistication of our understanding, and its fit with empirical data, we visualise these objects and processes using imagination, models and metaphors. Our challenge in teaching is to communicate our vision of objects and processes in such a way that we generate understanding and excitement while avoiding misconception.

Photosynthetic electron transport is a biological process that is complex, conceptually difficult, and a traditional source of confusion and misunderstanding in the classroom. Even more than respiratory electron transport, it involves understanding of diverse areas, including photophysics, redox chemistry, enzymology and membrane biophysics. Even to set the stage, students must conceptualise the thylakoid membrane, protein complexes embedded in this membrane and electron transport components bound to these proteins. Add to this the dynamic, multi-step processes of light harvesting, electron transport, proton pumping, and photophosphorylation, and it is not surprising that this area is an educational challenge.

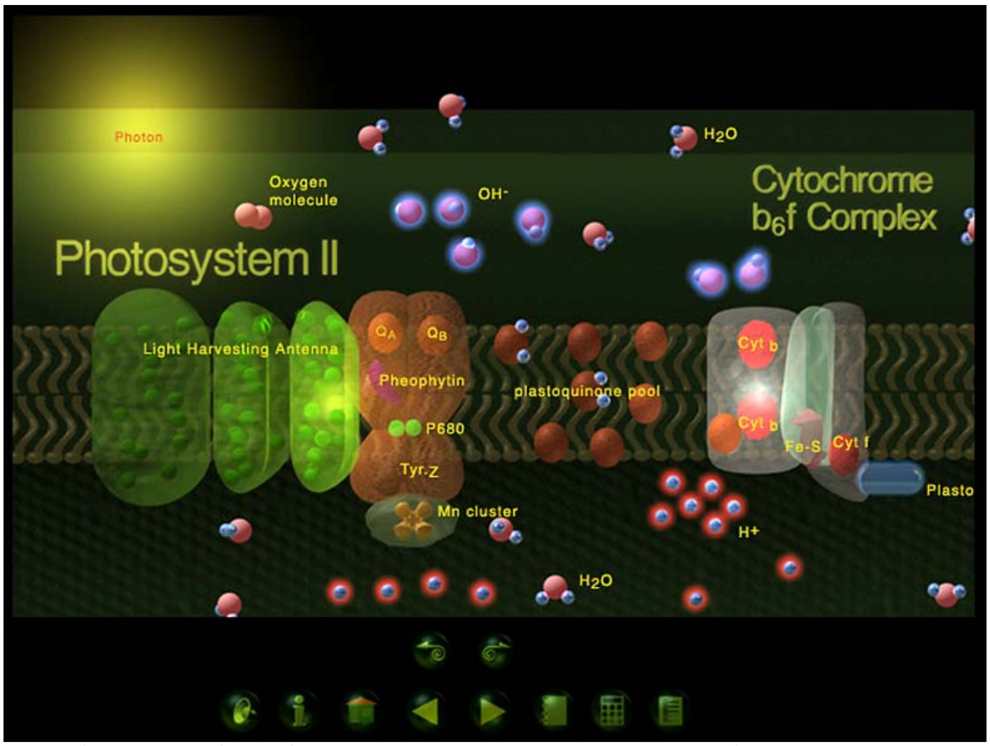

Fig. 2. *Screen shot of part of the photosynthetic electron transport chain from Module 3.*

We have presented photosynthetic electron transport as a 4-dimensional animation (Fig. 2), which combines up-to-date information about structure and function with attractive and exciting visual effects which we hope will enhance understanding, interest and recall. The animation avoids over-simplification and shows features such electron gating in PSII, the Q cycle of the cytochrome b_6f complex, and the binding change mechanism of the ATP synthase (Fig. 3). The entire chain is presented as four separate animations which students can explore at their own pace, with or without descriptive voice-over. The animations have been composed from a single panoramic view of the entire chain, and each animation, and the events associated with each protein complex, are clearly linked, so that connections and an integrated understanding of the chain can be gained. The animation is augmented by short descriptions of the complexes and electron transport components which can be viewed by students at any point as they work through the animations. There are also several introductory pages of text. In bringing together graphic design expertise and software with the inside knowledge of active researchers in the area, the module presents an imaginative and sophisticated view of this key process to students at all levels of tertiary education.

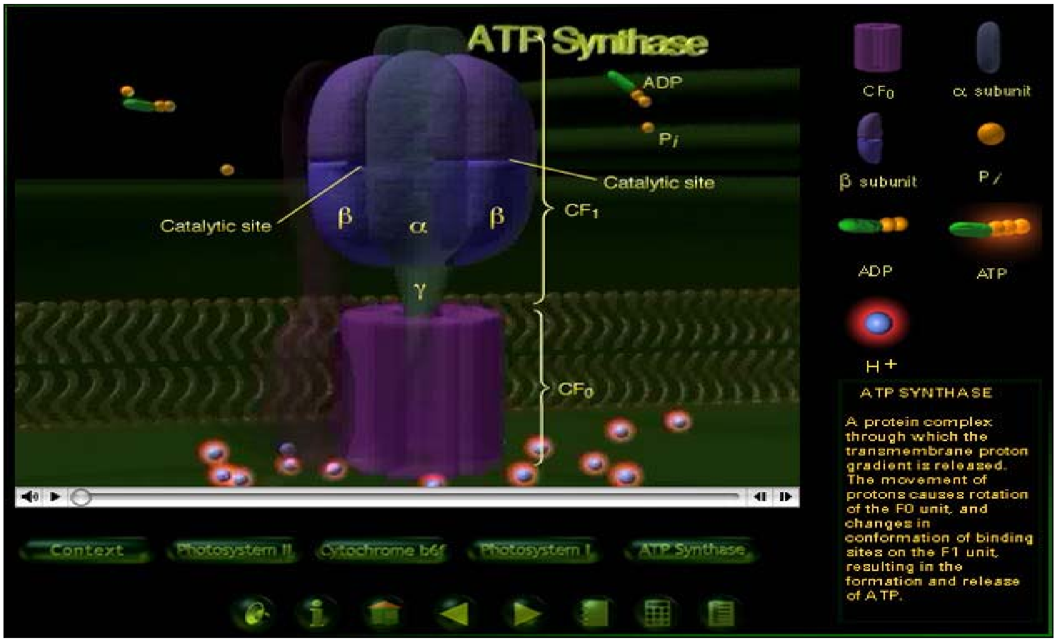

Fig. 3. *Screen shot of ATP synthase animation from Module 3.*

Evaluation

The major aim of this project was to increase understanding of core photosynthetic principles in introductory level biology and to facilitate understanding of equipment used in project work and in the wider world of scientific research at senior levels. Feedback from students has been sought for each module throughout the evaluation. Initially, subjective evaluations were used since these were most useful to us for identifying problems in the early versions of each module. However, since 2000 we have adopted a combined approach to evaluation which also allows us to gauge the improvement in modules more effectively. The questions asked and results for these evaluations are shown in Table 2. Consecutive surveys for Modules 4 and 5 have shown improvement in the latest versions. Our most recent evaluations show that >95% of students agree with a range of positive statements exploring both the functioning and attractiveness of the modules, and their effectiveness in supporting the subject and helping students to learn. More than 50% were strongly supportive of these statements (Table 3) and this is supported by comments received in University teaching evaluations where students have spontaneously indicated that the modules are one of the strengths of their third year physiology course.

Table 2. Summary of results from evaluation of Modules 1-3 & 5, showing version of module, number of students responding and mean response for each question (Module 3 has been used in lecture presentations only to date).

	Module and Version					
	M5 v.2	M5 v.3	M4 v.1	M4 v.2	M2 v.1	M1. v.3
Number of students surveyed	*10*	*17*	*17*	*17*	*29*	*51*
The concepts in this module were presented clearly and fully explained.	1.9	1.5	1.9	1.8	2.0	2.6
The content of this subject was presented at a level that was appropriate for my understanding.	1.8	1.7	N/A	1.6	2.0	2.0
The computer simulation enhanced my learning in this subject.	1.9	1.5	2.1	1.5	2.2	2.4
The computer simulation was used effectively to support the subject.	1.8	1.7	1.8	1.6	2.2	2.2
Using computers in the classroom to enhance the educational experience is valuable.	1.8	1.5	2.3	1.5	2.3	1.8
The graphic images were clear and appropriate.	2.2	1.6	1.7	1.6	1.9	1.9
The on-screen text was legible.	3.2	1.6	2.2	1.9	1.7	2.2
The on-screen text was concise and meaningful.	2.4	1.5	2.2	1.8	1.7	2.3
The computer-based materials used in this subject functioned properly.	2.0	1.5	1.6	1.7	1.8	1.7
The computer-based materials allowed me to practice what I had learned.	2.1	1.5	3.0	1.8	2.7	2.3
I was able to navigate easily through the content.	1.7	1.9	1.7	1.9	2.1	2.0
I had control over the pacing of content in this subject.	1.3	1.6	1.3	1.5	2.1	2.0
Overall mean	2.0	1.6	2.0	1.7	2.1	2.1

Responses:
1) Strongly agree, 2) Agree, 3) Mildly agree, 4) Mildly disagree, 5) Disagree, 6) Strongly disagree

As self-reporting by students as a sole method of evaluation can be problematic (Sinclair *et al*., 2004), we also sought evidence for the effects of use of the modules on students' learning outcomes. The fluorescence module has been successfully used at third year level for the past five years. Prior to its use, traditional delivery by lecture and practical to classes of up to 60 students was very unproductive. Testing of students (by examination and practical report writing) showed that the key concepts were poorly understood and students had difficulty relating to the practical objectives. Since the modules have been employed, student reports have demonstrated improved understanding of the basic concepts and in examinations, students are self-selecting essay questions relating to this module which previously were avoided. The quality of the examination responses is also much improved. Over the past 3 years the mean mark for short-answer questions containing material which was only covered in lectures was 43%, whereas with material that was fully supported by the modules, the mean increased significantly to 75% (Analysis of Variance, $F_{2,136} = 11.89$, $P<0.0001$). In addition, students have initiated the incorporation of chlorophyll fluorescence methodology into ecologically based Honours projects indicating that they have gained the confidence to add these techniques to their repertoire of skills.

Table 3. Summary of replies to open-ended questions from module evaluations. The data are number of responses of the type indicated. N = 17.

Q. What do you think are the strengths/ most valuable aspects of this module?	**Module 5**	**Module 4**
Clear/Well-explained/Easy to understand	5	4
Informative/relevant to lecture material	2	2
Broken down but comprehensive/Brings ideas together/Covers wide area		4
Follows on well/Easy to use/Good instructions	5	3
Ability to go back and forward	2	
Go at own pace	4	7
Effective/great displays and visuals	6	
Enhanced understanding of topic (explained practically)	5	4
Graphs good in simulation/Visuals and animations stimulating/Colour/Interactive	3	12
Graphs with explanations/interaction with text	1	6
Summaries		5

We believe that one of the strengths of the experimental modules is that they do not give in to the temptation to use the computer-based medium to create short-cuts for the students. The students are required to derive raw data and use the calculator and notebook to analyse and record this data which is stored in a flexible format compatible with data analysis software such as Excel. The computer does not do basic calculations for the students. As demonstrated by Sinclair *et al*. (2004), learning basic skills is a prerequisite to higher order learning, and skipping this step can destroy the benefits of this type of computer-assisted instruction.

The multimedia package has been commercially available for two years, and is currently in use in Universities in Australia, the UK, the United States, Spain, Portugal, Austria, Japan and Singapore. Since its production, the authors have received teaching awards from the Australian College of Education, the Australian Society of Plant Physiologists (now the Australian Society of Plant Scientists) and the American Society of Plant Biologists.

Application and Technical considerations

The package has been designed as a resource to augment classes and subjects. It was not designed to replace face-to-face teaching, to substitute for course design and curriculum development, nor as a distance education tool. A number of students commented in evaluations that the availability of the resource should not be used to justify reduced teacher-student contact. While we provide examples from laboratory manuals which illustrate how we utilize the modules, we do not include extensive study guides, in line with our desire to produce a flexible resource that can be integrated into a range of courses at different levels. We recommend that teachers develop their own questions and study guides to assist their students in using this resource for their particular learning needs. The way the modules are used will vary with the emphases, priorities and desired learning outcomes of the teacher, the curriculum in which they are embedded, and the learning environment into which they are integrated. Although the modules were designed for tertiary education, the experimental simulations in Module 1 are relevant to, and could be incorporated into, senior high school biology courses.

The modules can be accessed via a stand alone CD-ROM, that is available at a discounted rate for students, or made available using a server to create a virtual learning environment (VLE). The modules were designed using Macromedia Director 8 Multimedia Studio. The cross-platform CD-ROM will run on all modern Mac and IBM systems with Apple QuickTime. Some of the modules are also suitable for Web-based delivery.

Conclusions

This multimedia package – 'Photosynthesis *in silico'* - is an innovative resource for teaching the fascinating and fundamental process of photosynthesis. It can be used to augment lectures and tutorials; as an adjunct to experimental work; as stand-alone, self-paced modules in practical classes; and as a flexibly delivered course component for self-paced learning. We believe that it effectively addresses some of the fundamental challenges in photosynthesis education, both theoretical and practical. Importantly, it encourages students to visualise aspects of photosynthesis, and to comprehend the process deeply, without losing appreciation for its complexity. This is important in preventing and clearing up persistent biological misconceptions. A key contribution of the practical modules is that they ensure consistent practical outcomes to all students, regardless of class size. Ironically, the computer-based simulations may also bring students closer to 'real world' photosynthesis research. We hope that the existence of such resources may also help to reverse 'plant neglect in biology education' (Hershey, 1993).

For further information about 'Photosynthesis in silico' and to access an order form, visit our web page (http://www.uow.edu.au/science/biol/innovations/phis/).

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