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*An exploration of multimedia programs in the
teaching of photosynthesis*

Jeffrey William Beatty BSc (Hons.), MSc (Oxon.)

**Submitted for the degree of Doctor of Philosophy in Educational
Technology at the Open University, Milton Keynes**

March 2007

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Abstract

This thesis investigates the effectiveness of two multimedia programs in delivering an understanding of the light - dependent reaction of photosynthesis. One program, *Cells and Energy*, was adaptive, whilst the other, *Photosynthesis Explorer*, was interactive (a practical simulation). To inform the value of these different designs an empirical study was conducted. Ten pairs of participants were allocated to use one or other of the programs. During their use and with the researcher's support, members of each pair attempted to learn about the light-dependent reaction. Whilst doing so, audio and visual data were captured to provide information as to participants' and researcher's activities related to this learning process. Each participant's understanding was determined by matched pairs tests – as a pre-test and as immediate and delayed post-tests.

The programs generated a highly significant difference ($p < 0.0005$) amongst test results, with increased scores in the post-tests, but there was no significant difference between the programs on participants' performance. Nevertheless the *Photosynthesis Explorer* group took about three times as long to deliver this equivalent effect.

By employing Laurillard's Discourse Model for evaluating events, which were recorded during the programs' use, this research provided evidence of the importance of feedback as scaffolding and support in delivering knowledge and understanding. The recorded, as well as test, data revealed misconceptions. Their effects on learning were complex as were cognitive conflict episodes arising from them, whose resolution was multifaceted.

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Chapter 1 Introduction

1.1. Background to the thesis

The research in this thesis concerns the value of two different multimedia programs – one an adaptive / interactive / simulation hybrid, *Photosynthesis Explorer* and the other an adaptive / tutorial type, *Cells and Energy*, in the development of an understanding of the light-dependent reaction of photosynthesis.

Photosynthesis is an important scientific topic and is an essential metabolic process involved in the circulation and balance of carbon dioxide and oxygen in the atmosphere (Delpech 2006). It is particularly relevant to the current debate on global warming (Maslin 2004) as well as on sequestration of carbon in organic stores such as trees worldwide and dead plant matter in the Russian Tundra. Indeed, without oxygenic photosynthesis the earth could not have established either of the two stable steady states for atmospheric oxygen (Coldblatt et al. 2006). Students of biology in the U.K., at A-level and beyond, are required to understand the complex processes – physical, chemical as well as biological – that are involved in the pathways of photosynthesis. In addition, there is perhaps a need for the wider community to have a grasp of the process in the context of renewable energy, particularly with regard to the possibility of uncoupling photolysis of water from the reduction of carbon dioxide, in order that hydrogen becomes available as a replacement for fossil fuels.

However, in the educational world it is acknowledged that photosynthesis is difficult to understand (Stavy et al. 1987, Bahar et al. 1999, Indge 2000), particularly for students at an advanced stage since it is essential to comprehend aspects of the three sciences listed above at an abstract level. Therefore it is important to find ways in which this complex process can be understood both by those in an educational setting and by the wider community. One way of achieving this is through the use of computers, since they are widely available in schools, educational establishments generally and at home.

Computers have been widely publicised by Government for use in the classroom (Wellington 2003) and many children and even adults are daily in front of a computer for the purpose of learning. Indeed, there is a wide variety of pressures for increased use of Information and Communication Technology (ICT) in schools since it became a statutory requirement in all subjects with the introduction of the National Curriculum in 1989. Professional bodies such as the Association for Science Education through their publication *School Science Review* and charities, such as Futurelab in its *Futurelab* series advocate the value of computers in the school setting. Students, too, with their familiarity in using computers from an early age are willing to engage with computers in the learning process and Veen (2003) suggests that students are entering education with sound computer skills.

There are various forms of educational software that might enhance cognitive performance and some, such as data logging systems, data analysis software

and graphing tools may free the student from laborious and repetitive activities allowing more time for the development of cognition. Other types include interactive media (simulations, microworlds and models), hypermedia (hypertext and multimedia) and adaptive media (tutorial programs and systems), though the distinctions are often blurred. Today most programs are multimedia, though they may possess the characteristics of simulations, tutorial programs or indeed of any of the other types.

There is a wide diversity of opinion as to the value of the different types of computer program in encouraging different cognitive skills from those of investigation to that of concept development, especially where there are tensions between what might be considered sound pedagogical (and psychological) approaches to learning (Loveless et al., 2001, Wallace 2001, Osborne & Hennessy 2003, Denby 2003, Stein 2005) and the software (Marchionini 1995, Elissavet & Economides 2003, Lewis 2003) that is available to provide this understanding of specific subject areas, such as photosynthesis. In addition, the use of ICT may be resisted by teachers, not from a Luddite perspective of new technologies in the classroom, but from both a pedagogical one and lack of familiarity with what is available. The first problem that of pedagogy, considers the integration of the computer into a learning strategy, which is at present rarely seen (Osborne and Hennessy 2003) and the second relates to fitness of purpose of the program used.

With regard to pedagogy, Kerr 1991 (p. 121) suggested that *'if technology is to find a place in classroom practice, it must be examined in the context of*

classroom life as teachers live it. Nevertheless the pedagogical approaches in the classroom are evolutionary and the introduction of computers is a catalyst for change. However, teachers find it difficult to integrate computers into their lessons for a variety of reasons and these problems should not be underestimated. Certainly the use of ICT in secondary science increased considerably between 1998/9 and 1999/2000 according to DES, DFE and DfEE statistics from under 10% of schools in science to over 50%. However, the specific use of ICT in the classroom is not described in such reports. Nevertheless one indication of this is reported by Rogers and Finlayson (Rogers and Finlayson 2003) from the ten schools taking part in the Science Consortium NOF training, where 85% of the lessons using ICT were concerned with science knowledge and understanding and that 95% of teachers reported that *'their teaching objectives of lessons with [simulations] software were successfully achieved'* (p. 106). Whilst this may be so in schools with enthusiastic teachers working with a dedicated group promoting technology, many establishments in science are likely to restrict their use of ICT to the tried and tested in order to deliver targets set by external tests and examinations. Other practical considerations restricting the use of ICT are legion and include lack of adequate technical support (Schofield 1995) and resources. More importantly, perhaps, there are the teacher aspects, including a pedagogic style that focuses on the teacher (the transmission paradigm) as the disseminator of knowledge to one that is more student centred (the constructivist paradigm) focusing on the need of the individual as well as a lack of expertise in choosing the right software (if it is available) and deciding the right context for its use. As the Ofsted (2001 p. 12) report cited core

subject teachers '*select software packages for their visual appeal rather than their relevance to lessons*'. The general picture is, therefore that '*well-integrated and effective classroom use of ICT is currently rare*' (Osborne & Hennessy 2003, p. 5).

It is very confusing for teachers to select appropriate programs for particular purposes, since they vary from those that offer free (open) discovery, such as hypertext and open simulations to those that are highly constrained and are no more than drill and practice. Many authors suggest that different types of program are useful for the learner, including: Blaye et al. 1991, Geban et al. 1992, Laurillard 1993, O'Shea et al. 1993, Mevarech 1994, Hennessy et al. 1995 (a) and (b), Pilkington & Parker-Jones 1996, Williamson & Abraham 1996, Lutterschmidt & Schaefer 1997, Good & Berger 1998, Frear & Hirschbuhl 1999, McFarlane et al. 2000, LeBlanc et al. 2001, Sneddon et al. 2001, McFarlane & Sakellariou 2002, Osborne & Hennessy 2003, Reid et al. 2003, Ruthven et al. 2004. The reasons for their advocacy vary from the affective domain, such as the encouragement of collaboration between students (Sneddon et al. 2001) during the learning process to the cognitive domain, such as improved problem solving skills and the development of conceptual understanding. From the affective perspective, when students are working in pairs and in co-operation, using Integrated Learning Systems (a member of the adaptive media paradigm) they outperform others who are working individually (Mevarech 1994) just as they do when working with simulation programs (Blaye et al. 1991). But what of the value of different programs from the cognitive view point?

Hypertext programs that offer free discovery appear to have little value in the development of problem solving skills or in driving forward concept development, though they do have value in determining prior knowledge and misconceptions and in formative and summative assessment (McFarlane et al. 2000). Simulation programs are considered to be beneficial to students' ability to solve problems (Geban et al. 1992, Lutterschmidt & Schaefer 1997) and to develop more sophisticated reasoning skills (Hennessy). Some authors have commented on the value of simulations, particularly closed simulations in developing conceptual understanding (McFarlane & Sakellariou 2002, Ruthven et al. 2004) and with multimedia simulations of scientific processes (Osborne & Hennessy 2003, Frear & Hirshbuhl 1999) and, others on the value of more open programs (Reid et al.) and some in more general terms (O'Shea et al. 1993). According to Laurillard (1993, p. 162) types of adaptive media such as tutorial systems are the acme of computer programs, since *'they address all aspects of the learning process'*, which means that they correlate well with the pedagogic discourse model as advanced by her. However, they are criticised by Good & Berger (1998) among others who suggest that compared to science knowledge, knowledge of science teaching (the teaching strategy) and learning *'is soft and fuzzy'*. It is not surprising therefore that teachers are confused.

To add to this confusion most of the programs, except perhaps the most basic adaptive type, the tutorial program, which in essence is drill and practice, are called multimedia, in the sense that users can *'input, create, manipulate and output text, graphics, audio and video'* (Strothman 1991 in Galbreath 1992 p.

15). Moreover almost all multimedia programs include some kind of interactivity however limited in order to encourage reflection, to construct problem solving situations in a metacognitive way, to assimilate concepts, to use them in a variety of situations and to provide instruction that is specifically individual and stimulating (Leblanc et al. 2000).

Whilst many advocate these programs in the learning process, research results on the impact of the different types on conceptual gain by students using them are limited. One reason for this is that research on the effectiveness of multimedia programs often involves meta-analyses, which do not separate either the context in which computers are used, or the types of programs and often report changes in student attitude without any significant conceptual gain. However, de Jong & van Joolingen (1998) and Lee (1999) reported that simulations do produce measurable conceptual gains, but as described by Reid et al. (2003, p. 9) when *'comparing the effects of simulation-based learning to more traditional modes of learning [there is] little persuasive evidence in [their] favour'*. Other reasons include the approach taken in the measure of 'what learning' actually is and the context in which that learning takes place.

That learning takes place when computers are used is often measured psychometrically using for example the multiple choice test. However, such measures of knowledge and understanding are strictly limited and possibly invalid, since they fail to show how understanding or misconceptions have evolved during a learning programme. In other words the socio-cultural origins

of these ideas are unknown either for development or for remediation. For these evolving ideas to become communicable, interpersonal dialogue is necessary during the learning process and for terminal knowledge and understanding a test that interrogates conceptual change is required. This view of learning is compatible with that of Vygotsky.

1.2 Importance of the research

Whilst science teachers use computers in the classroom, there is limited evidence as to the value of the different tools available on student attainment in the classroom. Indeed a bibliography of 50 studies between 1994 and 2003 (Bell & Bell 2003) demonstrates that only a small minority relate to student achievement in science. Many workers in the field advocate learning by specific computer tools, be they drill and practice, tutorial, or simulation programs, but there are few comparative studies, as to their relative efficacy in delivering an understanding of specific topics.

Major limitations on the effectiveness of computers in the classroom may be the pedagogical approaches adopted by teachers (Webb 2005) such as working with their students in constructive and collaborative situations, as opposed to more didactic ones. There is a need to encourage teachers to modify their practices in order to make the computer a more effective learning tool.

One important consideration in any pedagogy is the prior knowledge that students bring to a topic under study. It is from this perspective that

photosynthesis is an ideal topic as the subject for this research, since misconceptions have been widely studied in the 11-16-age range, in this specific biological domain, but their effects on more mature students have not been investigated to any great extent.

1.3 Research questions

In light of the previous introduction on types of software, the pedagogic discourse model and the problems associated with school uptake of computers in the classroom, this research will address the following questions.

- What are the generic features of photosynthetic software that can support student learning?
- What are the pedagogical strengths and weaknesses in relation to the pedagogic discourse model?
- How can this model inform the construction of a support system to encourage an active teaching strategy in the classroom?
- How can these findings assist with recommendations for classroom teachers when evaluating and using different pieces of software that can be incorporated into a holistic teaching strategy?

1.4 Overview of the thesis

This research takes the constructivist view of learning based most particularly on the work of Vygotsky. It considers the construction of knowledge as a shared experience between students and between them and the researcher (Vygotsky 1978) and uses audio, video and hypercam evidence of the

dialogue to demonstrate successful episodes that realise the goal conceptions sought. The dialogue is also used to show when such episodes are less successful. These episodes are described in terms of Laurillard's discourse model (Laurillard 1993), conflict and its resolution (Linn & Barbules 1993), zones of proximal development (Vygotsky 1978) and scaffolding (Wood et al. 1976).

It outlines the important concepts that students need to understand about the light-dependent reaction of photosynthesis and the common misconceptions that students may hold at an earlier age and which may have a negative effect on the development of an understanding about the process at a more sophisticated level.

It reviews the programs that are available for disseminating knowledge and understanding about photosynthesis at a conceptual level commensurate with that expected either by examination boards in England and Wales for students in Year 13, or for first year undergraduates and selects two for further study.

A test is described that was designed as a result of a pilot study and the work of others principally Kinchin (2000) and was used to measure the extent of participants' understanding of the light-dependent reaction of photosynthesis prior to and as a result of the use of either of the two programs in the Main Study. In the Main Study the construction of knowledge when using the different programs is compared as well as their effectiveness in delivering an understanding of the light-dependent reaction.

The thesis is set out in the following chapters of which a summary is described below.

Chapter 2 reviews the work of Piaget and Vygotsky in the context of learning, the different types of computer program, research evidence of their effectiveness in the teaching of science and the relationship between the different programs and learning theory as well as the pedagogic discourse model, with specific reference to feedback.

Chapter 3 describes previous research on student learning about photosynthesis with specific emphasis on misconceptions together with evidence from fieldwork from A-level examinations and from student interviews about common misconceptions that student hold-post school instruction.

Chapter 4 provides details of the Pilot Study. It outlines the characteristics of the different programs, together with the reasons for selecting two dissimilar multimedia programs – a closed simulation, *Photosynthesis Explorer* with lots of interactive activity, animations and feedback on simulations as a result of manipulation of variables – a tutorial, *Cells and Energy* also with lots of interactive activity, animations, feedback on answers to questions, together with additional scaffolding and information. Reviews the results of the pilots on *Photosynthesis Explorer* and *Cells and Energy*, with specific reference to the use of *Photosynthesis Explorer* and the design of the test.

Chapter 5 describes the methodology, design and procedures of the Main Study. This includes the format, number and design of the tasks in the Task Booklet at both pre-A level and A-level. It provides a statistical overview on the effects of the two programs on participant knowledge and understanding about the light-dependent reaction as well as the mean average time spent by participants on each of the two programs.

Chapter 6 provides an analysis of participant task scores across the three tests on each of the tasks in the Task Booklet, with a comparison of performance between the two programs.

Chapter 7 examines the correlations of task scores with participants' comments on each task for a selection of pairs at each test stage – the pre-test, post-test and delayed post-test. This critically examines the relationship between the participants' confidence in their responses on the tasks and their written comments in terms of the target responses. The selected pairs were one from each of the following groups from each of the two programs: high scoring pair, a low scoring pair and a mixed one.

Chapter 8 investigates participant events during cognitive walkthroughs for the selected pairs and compares the duration of the different activities for each of the programs. It provides selected discourse for the three pairs of participants for each program to demonstrate the effects of dissonance and mutually supportive discourse, of working within

and outside zones of proximal development, misconceptions prior to and developed during discourse, of feedback and of pedagogic discourse between pairs and relating these to task scores and written comments.

Chapter 9 describes the achievement of the research in terms of the research questions, evaluates the findings and provides pointers for further research.

Table 1.1 Timetable of research

Year	Research activity	Outcomes	Chapter
1998-2001	Background research on the work of Piaget and Vygotsky and computer programs	Derivation of current concepts in learning psychology	2
	Background information on photosynthesis. Document search on previous work into learning about photosynthesis	Formulation of research question	3
	Fieldwork on misconceptions	Misconceptions held by Year 12 and 13 students through fieldwork	
2001-2002	Selection of software	<i>Photosynthesis Explorer</i> and <i>Cells and Energy</i> programs	4
	Pilot studies	Trials of <i>Photosynthesis Explorer</i> program Instructions changed from one of free discovery to one of guided discovery Evolution of test tasks	
2002 - 2003	Preparation of Task Booklet	Completion of task booklet	5
	Main Study	Collection of data during cognitive walkthroughs from forty participants	
2003 - 2004	Overall statistical analysis of data	Effects of the two programs as learning tools on the light-dependent reaction determined	5
2004 - 2005	Analysis of task performance on two programs	Overall cohort performance on different tasks within the task booklet in pre- post- and delayed post-test	6, 7
		Performance of selected participants on selected tasks	
2005 - 2006	Transposition of cognitive walkthroughs into categories	Determination of reasons for different levels of performance in terms of the program type and participant discourse	8
	Cognitive walkthrough discourse collected and analysed		
2006	Conclusions and summative evaluation	Effect of program type on student learning	9
		Advice for teachers on selection of programs for teaching conceptual understanding	
		Further work on multimedia programs	

Chapter 2 Learning using computers

2.1 Introduction

Computers are widely used and outside agencies, such as governments, promote their use in education. The computer has been harnessed to clarify data through the use of graphs and spreadsheets for many years. It has a particular role to play in the assistance of student recall of scientific concepts and teaching in general with the use of hypermedia, simulations, microworlds and adaptive media.

In order to assess the possible value of computers in aiding conceptual development and the promotion of problem solving skills particularly, it is necessary to find out, not only how different psychological theories assist our understanding of the learning process, but also how different ICT tools, from the technological and pedagogical points of view, may also assist it. This knowledge informed the research that needed to be undertaken in order to discover the set of tools that may enhance learning in photosynthesis and in other domains also, so that computer software design may be approached in a way that considers both learning theories and technological possibilities.

2.2 Constructivist theories of learning

2.2.1 Introduction

During the twentieth century learning theories have undergone dramatic changes in the western hemisphere. In the early part of the last century (at least until the 1950s), the behaviourist view of learning, as distinct from the cognitive and constructivist prevailed.

During the 1950's and 1960's, the Soviet advance in the field of space exploration, created an imperative in the western world to look at complex behaviours in the learning process, as distinct from reinforcement learning and quantitative measurement in the behaviourist tradition. This new paradigm called 'Constructivism' is based on the idea that the knower through mental activity constructed knowledge. Constructivism brought into play four main themes, cognitive development, concept development, the role of language and problem solving. Two advocates of this approach to learning – Piaget and Vygotsky – have greatly influenced the mode of instruction in schools and take different viewpoints on these themes. This research takes a specifically Vygotskian view of the learning process and expresses this below in three of the themes relevant to it – concept development, the role of language and problem solving. The other major theme of constructivists - cognitive development - is commented on but only where it is relevant to these three main themes, since in this research the stages of development in the sense of the maturation of cognitive function is not pertinent to student learning in the sixth form. Each section commences with the views of Piaget followed by those of Vygotsky.

2.2.2 Concept development and the role of language

For Piaget, learning new concepts depends on whether a new object can be incorporated within an already existing concept (or regularity), that is assimilation, whether the existing concept needs to be modified (accommodation), or whether it results in cognitive conflict (disequilibrium). This conflict could be an internal one, or develop when working with others creating dissonance. Piaget argued that as students work through conceptual

conflict, the negotiations that take place and the articulation of ideas that are produced with their peers lead to more cognitive constructions (Linn & Barbules 1993). Concept resolution, or assimilation, occurs as new knowledge is incorporated into the new concept. *'Conceptual change views however are likely to emphasise the transformations of conceptions in the process of learning. New ideas are not merely added to old ones; they interact with them, sometimes requiring the alteration of both'* (Strike & Posner 1985 p. 215).

The meaning of concepts in Vygotsky's view contains an important new element – the context in which generalisations develop. The progressive development of a concept is predetermined by the environment and by the meaning ascribed to words. Therefore the language of the environment will determine the way that a child's generalisation will take.

The importance of the process of concept formation (its construction), as distinct from the end product, led Vygotsky to hypothesise about the processes or stages of concept formation and consequently to the methods that might be devised to test how 'advanced' or meaningful a concept was. This is important, since at one extreme a child may simply, for example, produce a *'mechanical reproduction of a formula that has been imprinted, but not worked through... In another case, the definition may be the result of actual activity and persevering, logical work'* (Van der Veer & Valsiner 1994 p. 74).

Of fundamental importance to Vygotsky in the internalisation of a concept was the scientific concept. Such concepts, with their hierarchical system of

inter-relationships seems to be the medium within which mastery first develops to be later transferred to other concepts and other areas of thought. Reflective consciousness comes to the child through the gateway of scientific concepts, but these hold an important position in relation to other concepts, that is those regarded as spontaneous, which are developed outside the educational framework. *'It is our contention that the rudiment of systematisation first enters the child's mind by way of his contact with scientific concepts, and are then transferred to everyday concepts, changing their psychological structure from top down'* (Vygotsky 1962 p. 93).

For Piaget, language was important, since it externalised a child's understanding and provided the individual with an important, though not essential, tool for problem solving. For him, logic arises from action not language (Wood 1988). In general, Piaget was silent on the role of language in the construction of ideas and had little more to say on the subject, though he did deny that language had much to do with the development of logical or mathematical understanding – or with cognitive development in general. Indeed he lacked a formal standpoint on the role of language in logical thought (Piattelli-Palmarini 1980).

Vygotsky's view on the development, use and interpretation of language presents a quite unique approach that has implications for both teaching and learning. His approach assumes a much more important role for language than Piaget perceived. For Vygotsky, language is socially directed right at the outset and in its origins it is an instrument of thought. Nevertheless *'thought and speech have different roots...[which]...up to a certain point in*

time, follow different lines, independently of each other...[and]...at a certain point these lines meet, whereupon thought becomes verbal and speech rational' (Vygotsky 1962 p. 19). This thought process may result in new generalisations and concept development, but the language that describes them is not directly related to reality, but to inner speech which is social in its origins and therefore socially mediated. One implication of this view is that inner psychological functions are culturally, historically and institutionally specific. A second implication of having cultural mediation central to mind and mental development is that meaning of an action must be interpreted in context. The two are not inseparable. Concepts, and conceptual understanding are thus context specific.

If the meaning of the word and the development of scientific concepts are so important in concept formation and learning, then Vygotsky points the way to how these might be best achieved. For him, children (and even adults) can be guided by explanation, demonstration and in so doing reach higher levels of thinking if guided by a more competent and capable adult or a more knowledgeable peer. The expert is of fundamental importance to cognitive development and it is not an exaggeration to say that Vygotsky considers the expert 'other' as the main determinant of a child's total mental development. In order to explain this he introduced the term zone of proximal development (ZPD), which is the difference between the achievements of novices, be they children or adults, when they are assisted and when they are not. Vygotsky defines it as *'the distance between the actual developmental; level as determined by independent problem solving and the level of potential*

development as determined through problem solving under adult guidance or in collaboration with more capable peers' (Vygotsky 1978 p. 86). The expert achieves this development if he works within a novice's ZPD on a given task and most effectively if the expert works at the higher end of the learner's individual ZPD (Vygotsky 1978). To put it another way the lower end of the ZPDs range is the level of actual development (as could be measured in an IQ test) and at the higher end it is the level of potential development (Vasta et al. 1995). What this collaboration might consist of in detail, other than an emphasis on the role of communication, social interaction (Wertsch 1984, Vygotsky 1987) and instruction, *'through demonstration, leading questions, and by introducing the initial elements of a task's solution'* (Vygotsky 1987 p. 209) Vygotsky does not say. However, the work of Wertsch and others have provided greater focus on these issues. The effectiveness of bringing about learning within the ZPD depends on a number of factors, which include type and relevance of interaction (Cole & Wertsch 1996), quality of feedback, relevance of language, willingness of the expert to transfer strategic responsibility to the learner (Wertsch 1985) and the motivation that the learner brings to the task (Keller 1987). However, little is known about *'the successful transfer of task responsibility from adult to child'* (Diaz et al. 1990). The ability of the learner to internalise new concepts associated with a given task lies within this zone, which Vygotsky describes as the sensitive or optimal period for instruction and is dependent on complex factors, including biological, social and cultural. Thus the ZPD along with instruction provided within it are of fundamental importance in optimising abstraction, self-regulation, reflective consciousness and metacognition. Thus as the learner discusses a task with

an instructor, the learner internalises concepts and eventually not only completes the task independently (McGee & Richgels 1996) but also it [the instruction] '*....awakens and rouses to life an entire set of functions which are in the stage of maturation...*' (Mercer 1994, p. 103). The importance of this learner-apprentice relationship in learning is acknowledged by the fact that the unit of analysis should be the adult-child dyad rather than the individual child.

There are numerous studies on the relationships between novices and experts, Ellis & Rogoff 1986, McLane & Wertsch 1986, Wertsch & Hickmann 1987, Foot et al. 1990, Tudge 1990, Blaye et al. 1991, Mercer & Fisher 1992, Foreman & McPhail 1993, Rogoff 1995, Greene & Land 2000, Nassaji & Cumming 2000, Storch 2002 as well as Brown & Palinscar's seminal work, which showed that active discourse is most helpful with children in teaching reading where they have a partial grasp of the topic under investigation (Brown & Palinscar 1989). Rogoff (1990) hypothesised that there should be evidence of a change from other- to self-regulation [in a dyad situation] as children enter into effective guided participation.

The assistance provided by the adult has become generally known by the metaphor 'scaffolding', which springs directly from Vygotsky's mediated learning. Hausfather (1996) considers that there are at least two facets to this mediation. First there is scaffolding itself where the teacher must engage a child's interest, simplify tasks so that they are manageable (and within the ZPD) and motivate the child to pursue the instructional goal. Second, there is reciprocal teaching, where the teacher provides opportunities for dialogue

above and beyond merely asking questions, so that there is active participation in the discourse (Driscoll 1994). Scaffolding has been described and explained by many other authors, too, such as (Wood et al.1976, Maybin et al. 1992, Mercer 1995, Anghileri 2002). Wood et al. (1976, p. 90) write that *'This scaffolding consists essentially of the adult "controlling" those elements of the task that are initially beyond the learner's capacity, thus permitting him to concentrate upon and complete only those elements that are within his range of competence....It may result eventually, in development of task competence by the learner at a pace that would far outstrip his unassisted efforts.* As the metaphor of scaffolding implies, the support may be gradually removed, so that learning becomes predominantly metacognitive. Mercer (1994) states criteria for the demonstration of successful scaffolding, which are that it should not only enable children both to do something that they could not do unaided and eventually do on their own; but also provide evidence that a task is successfully completed both with the teacher's help and eventually unaided. This last criterion should be the major goal of scaffolding in teaching (Mercer & Fisher 1992) though there are often failures to hand over control (Edwards & Mercer 1987). The term scaffolding from this research point of view is perhaps best described as any event in planning, which might involve the sequencing of events surrounding a task, the methods for determination of the ZPD as well as the discourse, involving interactions and feedback that secures learning.

Studies demonstrating the influence of scaffolding in post-test performance include those by Wood & Middleton (1975) and Rojas-Drummond & Mercer

(2003). The ZPD and enhanced learning within it can be applied to situations where the learner is part of a dyad partnership, where the scaffolding is undertaken by an expert and the dialogue occurs between two learners at different development levels or at the same development level in which the dialogue is shared with an expert. If one of the learners in partnership dominates or the adult fails to transfer responsibility, the interaction is less successful (Driscoll 1994).

2.2.3 Problem solving and discovery learning

Problem solving activities and discovery learning are thought to play an important part in the learning of new knowledge. Piaget has much to say on the problem solving abilities of children and neo-Piagetians on the role of problem solving in general. He was less specific on discovery learning, though others used his ideas to justify learning by discovery. Problem solving is difficult to define though Barrows & Tamblyn (1980 p. 18) have attempted to do so. It is defined as *'The learning that results from the process of working towards an understanding or resolution of a problem. The problem is encountered first in the learning process and serves as a focus or stimulus for the application of problem-solving or reasoning skills, as well as for the search for or study of information or knowledge needed to understand the mechanisms responsible for the problem and how it might be resolved'*. Discovery learning on the other hand emphasises active learning, encouraging learners to ask their own questions, formulate hypotheses and carry out experiments on them. It is the learning activity that comes through free activity in a rich environment, only mildly structured by the teacher to

facilitate learning (Hilgard & Bower 1975). This idea of discovery learning is subsumed into the idea of progressive enquiry developed by Muukkonen et al. (2000), so that students treat new information as problematic (Bereiter & Scardamalia 1993) that needs to be explained by imitating the practices of research communities in Computer Supported Collaborative Learning (CSCL). Problem-based learning, discovery learning and methods of progressive enquiry have been heavily criticised by some authors, such as Kirschner et al. (2006).

Many who espouse the Piagetian perspective have fostered problem-solving techniques in the classroom, though Piaget himself did not propose a system of instruction based on his ideas. These developments are founded on the observation made by Piaget (Piaget 1928) that collaborative learning has a major role to play in constructive cognitive development. However, these collaborative activities are between students (rather than students and an expert other) and have been investigated by a number of researchers (Blaye et al. 1990, Tudge et al. 1996, Dori & Barak 2001, Ewing & Miller 2002, Williams et al. 2002, Hennessy et al. 2005).

Neither was he concerned with discovery learning per se, but in actions that would lead children to self-discovery by constructing knowledge for themselves. What children discover through their interactions with the world are discrepancies between their concepts of the way the world works and the actual outcomes of the operations they perform upon the physical world. In

other words disequilibrium and cognitive conflict would occur, with the assimilation of new ideas.

Vygotsky viewed problem-solving activities as a means of determining what individuals were capable of doing beyond that suggested by their mental age. Whilst he was essentially working with children, his thesis could equally apply to older individuals as well. For Vygotsky, *'The most essential feature of his [our] hypothesis is the notion that developmental processes do not coincide with learning processes. Rather, the developmental process lags behind the learning process; this sequence then results in zones of proximal development'* (Vygotsky 1978 p. 90).

2.2.4 Overview

In the outline discussion on the views of Piaget and Vygotsky, three principle aspects were discussed in terms of children's learning: concept development, the role of language and problem solving. Piaget is above all the initiator of modern ideas about developmental psychology, but his general theory of genetic epistemology neglected a number of key aspects of the learning process, which are outlined below. The strengths of his theory relate to concept development, regarding assimilation, accommodation and cognitive conflict – that is knowledge is about change and transformation and arises out of action – and generally at the higher levels of cognitive development, of abstract reflection creating opportunities of great leaps in understanding. The major weakness relates to the role of language. Piaget ascribed a minor role to language in the development of logic or in problem solving activities, so that as a consequence the final description of a child's understanding of ideas or

concepts is sufficient to describe the processes by which these achievements are realised. Thus in the Piagetian tradition research into children's learning focuses on children's achievements in pre- and post-tests, rather than on the interactions that take place along the way.

It is in the work of Vygotsky that the primacy of instruction comes to the fore. Vygotsky regards education, not only as central to cognitive development, but as the quintessential socio-cultural activity (Moll 1990). Since he places great emphasis on the notion that a person's understanding of a concept is associated with the meaning of words, the internalisation of concepts using language whose meaning carries historical, social and cultural attachments, the teacher or expert other becomes the centre of the learning process. Implicit in this is that the end product of the learning process is not the only, or even the best, measure of learning, but that the activities of the learner and expert in which it takes place are more important. One aspect of this is the value of the discourse that takes place in both determining and directing understanding, but the other is the pedagogy that instructs it. Part of this pedagogy is the expert's ability to determine a particular individual's ZPD on a specific task, to formulate a sequence of events that will best deliver learning and develop an evolutionary discourse that will address the learner's problems within the ZPD. Thus the focus of learning is not only or even mainly on the end product, but rather on the processes that lead to it. In consequence the effectiveness of both the scaffolding and the reciprocal interaction can be evaluated. In his view also, the internalisation of concepts to the level of reflective consciousness and abstraction that lead to self-regulation and metacognition is best delivered through scientific concepts.

From this review, what should be encouraged in an engaging educational setting? First, there must be recognition of each learner's cognitive development and conceptual understanding at the outset. Second, the expert needs to know the range of each learner's ZPD so that tasks are set at an appropriate level within it. Third, learning needs to be structured (scaffolded) towards the solution of a problem. Fourth, opportunities must be designed into the task in order to motivate the learner, to provide problem-solving activities with informative feedback, to encourage cognitive conflict, reflection and consequently abstraction. Fifth, the expert needs to know the level of assistance (mediation) required to create a dialogue between him and the learners that both informs the learning process and enables them to learn independently. Finally, the expert needs to be willing to transfer strategic responsibility to learners so that they have ownership of the process encouraging abstraction and metacognition.

Since the use of computers in the classroom for educational purposes has been extensively publicised by government over the past twenty five years (Wellington 2003) and since many children and even adults are daily in front of a computer screen for the purpose of learning, it is essential not only to discover the characteristic educational features, as outlined above, of different generic tools, but also to find out how effective they are in promoting learning and understanding. This is the subject of the next section.

2.3 The computer as an educational tool

2.3.1 Introduction

Whilst computers are widely employed in schools, there are a number of important questions that need to be considered about them if learning is to be effective when they are employed. These are:

- Why use them at all?
- What are the generic ICT tools that are employed?
- What educational values have the different tools?
- What is the relationship between psychology and instructional design?

Some researchers have written about computing in secondary and higher education science teaching, suggesting that there are tensions between what might be considered sound pedagogical approaches to learning (Rogers 2002, Denby 2003 and Osborne & Hennessy 2003) and the software (Lewis 2003) that can provide a sound understanding of a subject area, such as photosynthesis. There are various forms of educational software that might enhance learning from those that offer free discovery, such as hypertext and simulations, to those that are frequently used in Integrated Learning Systems (ILSs), which some have described as involving no more than test and practice exercises (Osin & Lesgold 1996). Nevertheless hypertext systems are difficult to use in the hands of a novice (Conklin 1987, Dillon 1991, Lawless & Brown 1997, Scherly et al. 2000) and possess the critical problems of getting lost or disorientated during navigation through the system (Marchionini 1988 and 1995), of insecurity in accessing the material or of comprehending what to do (Hammond & Allinson 1989) and of inadequate learning strategies. As Marchionini (1988, p. 10) explains, '*Users explore and*

then forget where they are and how they arrived.....[this freedom] to learn is not a sufficient condition to assure learning.....[it] can be confusing because [hypertext] increases decision making load [so that] cognitive resources may be diverted from content and relationships'. Hypertext might, therefore, appear to have relatively little value in the learning process. Simulations are also problematic for many learners, since learners using these tools often have insufficient ability to generate hypotheses (Chinn & Brewer 1993) or to modify these in the light of data gathered (Dunbar 1993). Whilst ILSs provide networks that are often easier to use by learners, they appear to have little effect on their understanding (Wood et al. 1999), because they often lack any opportunity for constructivist input from the learner (du Boulay & Luckin 1999), since they effectively use test and practice programs, so that performance on post-tests or mandated competency tests will reflect progress. The theoretical underpinning of ILS products is in neo-behaviourist learning theory, so that tasks are selected and feedback provided. Nevertheless when pairs are working together co-operatively they outperform others who work individually (Mevarech 1994).

The section below discusses the various types of software available, the research findings about their value in teaching and learning and finally makes suggestions about software design.

2.3.2 Why use computers?

In the sciences and mathematics there is much research that informs the reader as to the value of computers in the classroom. A number of papers are

listed below, together with a brief summary of some of them that describe the attributes or problems associated with particular program types.

A number of authors have suggested advantages to using computers in the classroom that range from conceptual understanding by learners to pedagogical practice in schools. Many of the papers emanate from studies in maths and science. However, it is in the sciences that there is a plethora promoting their use.

Some report on the importance of the immediacy of feedback. In this respect, Frost (1997) promotes the role of information handling technology by data logging. He cites the value of this tool is the immediacy with which observation can be transferred to manipulation of data collected during practical exercises and, in addition, to make links with other information and to make predictions.

Newton (1997) and Newton & Rogers (2003) suggest that the benefits of computers may be considered within the cognitive, affective and pedagogical domains. So far as attitudes are concerned, computers may stimulate enthusiasm, self-confidence, interest, time spent on task and other motivational aspects. It is also suggested that teachers are encouraged to think about teaching and learning when students are engaged in computer work. In a large study (Kozma 2003) involving 28 countries (though not exclusively on science practice in schools) it was found that computers were changing pedagogical practices, so that teachers were becoming more constructivist in their approach to student learning.

As well as there being gains in student attitudes and in teaching practice, what of cognition itself? Salomon et al. (1991) suggest that within the cognitive domain, the impact of computers can be considered as *'the effect with and effects of technology'*. With regard to effects with technology there can be enhanced performance on a task carried out with the aid of technology, because the emphasis during a task is to provide scope for interpretation, rather than on multiple computations. So, in Rogers's (1997) data logging exercises regarding scientific experiments, the student is gainfully employed on interpretation and reflection, rather than on manipulation of data. Denby (2003 p. 41) further emphasises this role of the computer, *'Computers also allow repetitive tasks to be carried out quickly and accurately so that more student time can be spent on thinking about scientific data generated'*. Ohlsson (1993) emphasises that the strongest argument for the use of the computer in education is its potential to provide individualised instruction. This is also what Saloman et al. (1991) call the *'effects of technology'* assisting in higher level learning outcomes. Nevertheless Bell & Bell (2003) produced a bibliography of over 50 articles (between 1994 and 2003) on the effects of ICT use at K-12, which carried only a small minority that provided any evidence of the effects of ICT on students' attainment.

2.3.3 Classification of ICT (Information and Communications Technology) tools

2.3.3.1 Introduction

In order to assess the strengths and weaknesses of the ICT tools available it is possible to classify them according to usage. In fact, a number of

classifications of ICT tools are in current use, such as Rodriguez (1997), Good & Berger (1998) and Laurillard (1993).

The most powerful classification is that of Laurillard. She lists the following groups: audio-visual media, hypermedia, interactive media and adaptive media as having particular, though variable strengths in promoting understanding. Audiovisual media include print, audiocassette, audio-vision, broadcast television or film and videocassette. Hypermedia includes hypertext and multimedia (in hypertext mode), interactive media are subdivided into simulations, microworlds and modelling; adaptive media contain the elements tutorial programs, tutorial simulations and tutorial systems (intelligent tutoring systems (ITSs)). Other authors have variously described these tutoring systems as intelligent education systems (Cumming 1993) and Integrated Learning Systems (ILSs) (Rodriguez 1997).

There is some disagreement about terms, but Laurillard's classification and sequencing is used below, since it provides a suitable platform from which to discuss the merits of different systems from the technological and pedagogical points of view, when concerned with conceptual gain and reasoning skill. Nevertheless the discussion will focus on the types of tools used in this research and audiovisual material will not be included, since the survey is exclusively concerned with the computer as a mediational tool.

2.3.3.2 Hypermedia

The current notion of hypermedia is formed from two different fields and it is informative to explain these. One is multimedia and the other is hypertext, which results in an imprecise definition (Burton et al. 1995). Multimedia itself

refers to different forms of media be they pictures, text, sound, animation, music and full motion picture. It was originally simply a presentation of some or all of these different forms. Hypertext refers to interrelated informational elements (nodes) in text mode that are accessible to the learner based on an expert's sequencing and linking of nodes, though learners are free to access the information in the order most appropriate for their purposes. The current usage of the term multimedia in the literature is, therefore imprecise. However, in general it is a method of designing and integrating computer technologies on a single platform that enables the end-user to input, create, manipulate and output text, graphics, audio and video, utilising a single interface (Strothman 1991). In some multimedia software, students use the various functions to recreate the learning that was originally in the author's mind. Consequently learners travel a pre-selected trail to concept attainment and are rewarded along the way with feedback, scores and supportive text, which enable interactivity (as for example the *Cells and Energy* program in the present research). In another form, the multimedia elements are within hypermedia environments (environments that allow the user to browse) so that the learner can exercise choice in the learning process (as for example the *Explorer™* Photosynthesis program in the present research). Learning is not necessarily achieved sequentially and allows greater independence on the part of the learner. The terms hypertext, hypermedia and multimedia are often used synonymously, but today hypertext refers to textual materials only and multimedia is used for software that includes a variety of media whether or not it is designed for sequential operation.

2.3.3.3 Interactive media

Interactive media involve feedback from students' actions. The decision about topic focus is the students' not the teacher's, since the teacher is not (necessarily) aware of the students' levels of understanding. There are three types: simulations, microworlds and models, only the first two of which are discussed. In science they are usually based on interactive graphics and provide the learner with the ability to visualise a process and investigate the effects of changing an independent variable on the dependent. Microworlds differ from simulations in that feedback provides comment on their description of the action, which can then be modified accordingly. The students' actions can be captured for inspection, reflection and revision and thus provide a problem solving environment. The *Explorer*[™] program possesses the characteristics of a simulation program, but also some features of a microworld, since students' work can be made available to the teacher via a portfolio file, modified and then returned to the user as extrinsic feedback.

2.3.3.4 Adaptive media

Adaptive media differ from the previous forms because they embody an explicit teaching strategy. They transparently attempt to emulate a teacher and to develop a one-to-one dialogue between the computer and the student. Laurillard identifies three kinds: tutorial programs tutorial simulations and tutorial systems. In tutorial programs, there is an intention to make a student's conception available to the program and multiple-choice tasks are provided, which are generally designed to elicit misconceptions. The program adapts to a student's answers on the basis of the knowledge revealed. In essence the *Cells and Energy* program is a tutorial. Tutorial simulations are a combination

of two complementary media, one adaptive and the other interactive. Tutorial systems (ITSs) have three components: domain knowledge, knowledge of the learner and teacher knowledge.

2.3.4 Value of hypermedia, simulations, microworlds and tutorial programs

2.3.4.1 Introduction

Laurillard suggests an ideal learning procedure by which students come to learn, to know, to understand, to solve problems and eventually to become metacognitive and self regulatory. It is used in this research as a standard (the 'ideal learning discourse') by which the merits of the various types of programs may be assessed in terms of tools aiding students' conceptual understanding. Nevertheless the discussion developed below includes comments by other authors who have made particular claims for the different systems employed and which are relevant to this research, be they hypertext, simulations, microworlds or tutorials. Laurillard is fully aware of the possible limits of the discourse model, since according to her: *'We cannot claim to have sorted out once and for all what students need to be told if they are to make sense of topic X....'* (Laurillard 1993, p. 84).

Nevertheless she suggests that an efficient learning procedure should be discursive, adaptive, interactive and reflective and that this needs to involve the teacher and student in the activities summarised in Table 2.1 below.

Aspects of the learning process	Student's role	Teacher's role
Apprehending structure	Look for structure Discern topic goal	Explain phenomena Clarify structure Negotiate topic goal
Integrating parts	Translate and interpret forms of representation Relate goal to structure of discourse	Offer mappings Ask about internal relations
Acting on descriptions	Derive implications Solve problems, test hypotheses, and to produce descriptions	Elicit descriptions Compare descriptions Highlight inconsistencies
Using feedback	Link teacher's re-description to relation between action and goal to produce a new description	Provide re-description Elicit new description Support linking processes
Reflecting on goal-action-feedback	Engage with goal Relate to actions and feedback	Prompt reflection Support reflection on goal-action-feedback

Table 2.1 The role of student and teacher in the learning process (Laurillard p. 86)

An important component of the above process, which is stressed by Laurillard is that of feedback, in which students offer their descriptions of what they have come to understand in their own way, as well as external feedback provided by a tutor or program in response to students' actions. Many authors report on the importance of this second aspect of feedback. Hattie (1987), Tharp & Gallimore (1988), Schimmel (1988), Tudge et al 1996, Black & Wiliam (1998), Gordijn & Nijhof 2002, Gibbs & Simpson (2004 and in press), Hennessy et al. (2005) and Whitelock (1999 and 2006) emphasise the value and effects of feedback on the learning process. Black & Wiliam (1998) and Hattie (1987) in reviews of what makes a difference to student achievement highlight the single most important factor, which is feedback. Schimmel (1988) states three types of extrinsic feedback – that which simply confirms that an answer is correct or not, provides a correct answer, or gives explanatory feedback, with a correct solution or with helpful comments that assist in correcting a wrong response. This last aspect merges into what has been described as

scaffolding and which Tharp & Gallimore (1988) identify as '*assisting and assessing performance*' using '*questioning and feedback*'. Hennessy et al. (2005, p. 266) describe this as an '*understanding of the skills and knowledge needed to handle the situation independently, and is used in generating feedback and tailoring the tutoring approach according to the learner's responses*'. Gibbs & Simpson (2004) and Whitelock (2006) report on the importance of feedback in formative assessment and Gibbs and Simpson (in press) on the importance of immediate feedback. They also stipulate seven aspects of feedback that will improve student performance. Tudge et al. (1996) and Gordijn & Nijhof (2002) investigated the complex effects of feedback on learning, which in the first case relates to the effects of working with and without a partner and in the second to the variety of feedback received. In Tudge's study, children receiving feedback improved more significantly than those who did not, but the presence of a partner was only beneficial when children received no feedback. Gordijn and Nijhof's study suggested that computer-based immediate feedback that affirmed or rejected a student answer, provided the correct answer (if it was wrong), an explanation and interactive teaching was no more effective than without interactive teaching.

How then could the tools under investigation encourage the development of a dialogue that includes feedback and perhaps to their success in encouraging learners towards a conceptual understanding of photosynthesis, which is one of the questions of this research and what have other authors said about their value in the learning process?

2.3.4.2 Hypermedia

Within this category, both hypertext and the type of multimedia programs derived from hypertext will be considered. From the perspective of the 'ideal learning discourse', hypertext has limited use, because it is not interactive. There is little if any descriptive feedback on the users' actions and very few reflective opportunities either. It reduces knowledge to information only, since the user is unable to interrogate the information in any way so as to internalise it by entering into some kind of dialogue, since the program is not adaptive and does not enable interaction or reflection. In the hands of someone who has knowledge on a topic, it has worth (Jenkins et al. 2003), but for the novice trying to make sense of the world it has limited value, since experts possess a mental representation (the big picture) of a topic, whereas novices generally do not (Spires & Donley 1998). All it really requires the student to do is to describe what he has seen, which may be identical to that originally perceived (Scherly et al. 2000). It is, though, possible to operate hypermedia in order provide vital clues not only about what it is that the student knows at the start (preconceived ideas and misconceptions), but also about possible routes that the student might take in order to enhance understanding. Multimedia programs of the non-sequential type go somewhat further, since the student can call on additional data that may be outside the 'text' in order to reach a firm conclusion or a partial one. According to Barron & Goldman (1994), this allows students to organise their knowledge in a way that facilitates its retention and transfer. There is, therefore, some additional value from and interaction between the medium and the student, but the medium, Laurillard suggests, is neither adaptive nor reflective. Leblanc et al. (2001) are more

positive about their value suggesting that the principles underpinning multimedia design do include interactivity in order to encourage reflection, to construct problem solving situations in a metacognitive way, to assimilate concepts, to use them in a variety of situations and to provide instruction that is specifically individual and stimulating.

Other sources of support for the view that a degree of reflection is to be found in these systems emanate from various authors in the 1990's, such as Blackmore & Britt (1993), Sewell et al. (1995) and Rodriguez (1997). However, Marchionini (1988) reflects Laurillard's disdain for such systems by registering concern that students suffer from cognitive overload and disorientation when using them. Marchionini (1988) considers that students may become overwhelmed, not only because of the concentration required to maintain several paths simultaneously, but also because of the volume of information handled and the number of decisions to be made.

2.3.4.3 Simulations and microworlds

Whilst interactive media are a considerable step forward, and microworlds address many of Laurillard's learning facets, it is suggested that neither is a complete learning tool, since they do not overtly tackle the question of concept development. Since students are not expected to make their concepts known, these systems are not discursive, but they are very interactive in the sense that they give intrinsic feedback (in simulations) and extrinsic feedback (in microworlds). Microworlds are especially interactive since they provide comments on students' descriptions, so that they can be captured for inspection, reflection and revision and, since the system encourages reflection

on the interactions that take place whilst the program is being run. Microworlds are, therefore, in terms of learning discourse a considerable advance.

With simulations interaction is not generally at the level of descriptions, rather the feedback is usually in the form of graphical and numerical data in practical simulations (intrinsic feedback) and any descriptive feedback is supplied externally. Neither do they encourage reflection, which is another prerequisite of sound learning. Nevertheless such opportunities can be added by the provision of work sheets, or in written exercises on the simulation, including a laboratory report - both of which assist the teacher in making worthwhile comments on their written work. Nevertheless a number of authors have commented on particular problems associated with simulations either in the context of practical simulations and discovery learning (de Jong & van Joolingen 1998, Vreman-de Olde & de Jong 2006), web-based simulations and discovery learning (Pedaste & Sarapuu 2006) and (Kirschner et al. 2006) discovery learning per se. De Jong & Van Joolingen (1998), Pedaste & Sarapuu (2006) and Vreman & de Jong (2006) refer to difficulties such as hypothesis generation and data interpretation, whereas Kirschner et al. (2006) criticise discovery learning from the cognitive perspective. They consider that whilst working memory is being utilised to search for information long-term memory is hardly employed.

In their original forms, simulations appear to have little effect on conceptual understanding and many researchers have advocated their use for other reasons. For example, Dewhurst et al. (1988), describing two simulations on

nerve physiology and frog heart, and Dewhurst et al. (1989) on genetic engineering, claim little for these programs in terms of conceptual development. Scanlon et al. (1993) consider that the value of simulations lies in their ability to demonstrate practical work that would not normally be possible in a laboratory for a variety of reasons, including safety, access and magnitude, or time constraints. Lutterschmidt & Schaefer (1997) suggest specific intellectual gains in a general sense on the Bloomian taxonomy to include knowledge and comprehension as well as application and analysis level skills provided that learning was through discovery. Nevertheless, the Puckland (Whitelock et al. 1991(a)) simulation does offer intellectual gain because it carries feedback and forces students to make predictions.

Nickerson (1995) describes the value of microworlds as does White (1984). They emphasise that this type of computer system can be built so as to challenge students' understanding of physical phenomena by contrasting naïve conceptions with those formulated say within Newtonian physics. There is, therefore, cognitive conflict here, which is an essential ingredient in the constructivists' canon. Like the previously mentioned simulations in biology, microworlds enable things to be seen that are difficult to observe because they are long-term or simply because they are not observable in nature. Take, for example, force and momentum – both abstract concepts – that can never be observed, but can be made visible and manipulated in microworlds (Snir et al. 1995). Saljo (1996) emphasises that microworlds not only allow new forms of interactivity, but they can provoke active reflection on the part of the learner, and hence encourage reasoning, problem solving and conceptual development. More recently Masson & Vasquez-Abad (2006) propose their

use for the demonstration of conceptual change in science using an historical microworld, once again in relation to Newtonian physics.

2.3.4.4 Tutorial programs

Laurillard suggests that the advantage of adaptive media, most particularly tutoring systems, is their possibility of coming close to covering all aspects of the learning process. Thus such programs should basically be able to *'specify a learning objective, offer a brief introduction to a topic, set a task according to a strategy for achieving that objective, interpret the student's performance on the task, use this to select the appropriate feedback, use the student's performance so far to select the next task'* (Laurillard 1993 p. 148). Tutorial programs cover all the above attributes, and usually elicit student misconceptions using the multiple-choice test (mct). The programs can be fully controllable by the students themselves and, very importantly, they provide program feedback but, Laurillard suggests, do not really assist conceptual understanding, especially in students who are experiencing conceptual difficulties. Within these systems, there are strategies for responding to students' responses; they can hold a database for logging student performance, and can respond by providing more practice. The Open University's multimedia *Cells and Energy* program carries many of the attributes of a tutorial program.

2.3.5 Research findings

2.3.5.1 Introduction

People are using computers more and more and, whilst there is considerable research data suggesting their effectiveness when used, the varied methods

of evaluation often result in quite different effects on student knowledge, understanding, problem-solving skills and attitudes. The most notable effects are on student attitudes, rather than conceptual gain (Webb 2005). One study by Blackmore & Britt (1993), reported below, showed that students were more enthused when using computers compared to traditional methods of teaching, but their understanding was not significantly improved as determined by using a multiple choice test. This might merely be because the measuring device for determining academic gain was the multiple-choice test. It is perhaps essential that evaluations of software employ a much wider variety of 'tests', as set out in Whitelock (2000 and 2001).

A number of meta-analyses have demonstrated the effects of computers on learning. For example, Kozma (2003) undertook one on technological activity in 28 countries that included 174 case studies of individual schools. The majority of these were from science of which about half were from biology. The major effects on children, as reported by teachers, were positive attitudes, new subject knowledge and increased collaborative skills. However, only a minority reported that students acquired informational handling and problem-solving skills. Recent meta-analyses in the U. K. also suggest that computer use is resulting in improved attainment. Results from Ofsted inspections' data in 1998, 1999 and 2000 (Becta 2001) from 409 secondary schools demonstrated a positive effect in science attainment when schools with good computer provision were compared with those that had not. However, what does the research suggest about the effects of specific types of software?

2.3.5.2 Hypermedia

If, as Laurillard suggests, hypermedia have limited value from the learning point of view, except in the hands of an expert, then this seems to be generally borne out by the research evidence that is available. Clark & Craig (1992) investigating several meta-analyses of multimedia [hypermedia] use produced results suggesting that multimedia programs were not effective in learning. More recent studies, such as Liao's (1999) meta-analysis on student achievement, demonstrated that their effects were mixed and Shapiro & Neiderhauser's (2004) review concluded that the majority of studies demonstrated very little learning. Beichner (1994) in an investigation in which multimedia editing was used found that students worked co-operatively, were motivated, and were able to find science content material from various sources to create a package for their audience. The students were concerned both with the accuracy of the information as well as its visual impact. Blackmore & Britt (1993), in a study using hypermedia based learning materials in the teaching of introductory cell biology to undergraduate students revealed that the tutorial created by them had been both stimulating and worthwhile. However the multiple choice assessment test used to compare this experimental group with a control group suggested that the computer-mediated tutorial created did not provide any enhancement to learning. A more recent study, Azevedo & Cromley (2004), suggest that hypermedia programs are effective in enhancing understanding if students' are trained to regulate their learning.

2.3.5.3 Simulations and microworlds

Simulation exercises have been available for many years in various subjects and some teachers have much experience in using, them, even from the days of the BBC computer in the UK. Dewhurst et al. (1988), Dewhurst et al. (1989) and Bowker & Randerson (1989) in the U.K. and Bork & Robson (1972) and Cavin & Lagowski (1978) in the U.S.A. report on their use and value in the sciences.

Lunetta & Hofstein (1981) in their review of research into simulations concluded that relatively little was known about the effects of simulations on science learning. Nevertheless since that time a number of research studies have been undertaken, which make claims for improved reasoning skills (particularly Geban et al.1992, Lazarowitz & Huppert 1993, Jiang & Potter 1994, Hennesy et al. 1995, Huppert et al. 2002, Tsui & Treagust 2003) attainment (particularly O`Shea et al. 1993, Williamson & Abraham 1995, Pilkington & Grierson 1996, Barnea & Dori 1999, Akpan & Andre 2000, Jimoyiannis & Komis 2001, Sneddon et al. 2001) and attainment in relation to misconceptions, socio-co-construction and conflict resolution (Law & Lee 2004), some of which are reported below. Indeed, because simulation programs now offer dialogues between the student users and the computer, and can possibly develop this with a specific pedagogical slant, these recent evaluations may be reporting on some real gains that are being made (Whitelock et al. 1991b), as for example Manlove et al. (2006). Geban et al. (1992) showed that students using the simulation problem solving approach demonstrated significantly greater achievement in chemistry and science process skills, as did the Lazarowitz & Huppert (1993) study in science.

Hennesy et al. (1995 (b)) evaluated assimilation on mechanics used with 12-13 year-olds and found that these students showed more sophisticated reasoning than other groups. Tsui & Treagust (2003) using a *BioLogica* program on genetics demonstrated improved reasoning skills by students in genetics.

O'Shea et al. (1993) prepared a simulation package which was used for pupils aged 10-15 to conduct experiments in physics. Their findings suggest that in a relatively short period of time a significant amount of conceptual change was detected. Williamson & Abraham (1995, p. 532) indicated that *'treatment with animations may increase conceptual understanding by promoting the formation of dynamic mental models of the phenomena'*. Pilkington & Grierson (1996) demonstrated the ability of students to generate explanations using simulation packages, though only as a result of hyper-media links to reference material. Sneddon et al. (2001) reported that a multimedia simulations program that replaced lectures in an undergraduate science module provided attitude benefits, such as *'enhanced co-operation [and] group work'* (p. 7), but also improved problem-solving skills and learning. However, the introduction of multimedia was only one of a number of reforms introduced to teach this particular topic – such as support workshops where students worked in groups so that *'it was not possible to establish the precise causal relationships for improved student performance'* (p. 10). Law & Lee (2004) also working with university students, but in groups of two or three, found that a simulation program on genetics encouraged them to make explicit their intuitive assumptions and to create hypotheses, in a socio-co-

constructivist environment, which was rich with misconceptions and conflict resolution

2.3.5.4 Tutorial programs

Specific research studies involving the use of adaptive media are extremely rare. There is a great deal of research, however, on ILSs, but the programs within them are ill defined and the majority of research is tainted by conflict of interest, since it is conducted by the companies marketing the products (Bentley 1991) and Jervis & Gkolia (2005) report on one school's negative experience with such systems. Dewhurst et al. (2000) reports on a study using a tutorial system that was designed to cover the cardiovascular physiology component at Leeds Metropolitan University. Students performed equally well in this final test whether or not they had undertaken this component of the course using the tutorial program or by more traditional methods.

2.3.6 Discussion

Most types of computer tools available for learning have been described in this section together with the value ascribed to those that are relevant to this work by researchers in the field. Various authors of research papers have noted the value and the possible pitfalls when using these different types of program, but from Laurillard's perspective none of the types provide all the necessary requirements for learning.

Whilst adaptive media may fulfil many of the attributes of the discourse model espoused by Laurillard and therefore offer the most efficacious tool available for enhancing conceptual understanding, they may be far too prescriptive, far too behaviourist in overtone, so that these systems, whilst providing students

with a step by step approach to their learning (which may be appealing from a certain pedagogical perspective – that is a traditional model of teaching and learning) may embody either a very limited view (the tutorial program), or one that is limited to an extent (the tutorial system) of what it is to learn science or any other domain. However, with suitable scaffolding, feedback and multimedia presentations that enable the visualisation of events some or all of these limitations could be minimised. Tutorial programs may, as Laurillard suggests, provide opportunities for an ideal discourse, though du Boulay and Luckin (1999) offer a word of warning '*.....but no amount of colourful routing can mask their failure to encourage the meaning of concepts or their potential role in the world*' (du Boulay & Luckin, 1999, p. 209). They are, perhaps, weak in developing either students' conceptual understanding or in developing problem solving skills. Nevertheless it is suggested that tutoring systems, such as intelligent learning systems (Koedinger et al 1997), do offer opportunities for discussion in the classroom, so that the wider aspects of what is being learnt may be considered.

Again according to Laurillard, interactive media have some merit in aiding conceptual development. However, they fail to address questions of feedback other than intrinsically in practical simulations on the results of experiments and do not encourage student description that spans across experimental findings and conceptual understanding. On the other hand, as some researchers suggest, they may encourage problem-solving skills, but reports often support Laurillard's view that they are not consistently effective in developing students' conceptual understanding (Reid et al. 2003). Nevertheless, it is possible that they, especially with the incorporation of

multimedia facilities (Pilkington and Grierson 1996) and greater interaction, offer opportunities to visualise events and encourage improved conceptual learning.

Hypermedia programs have potential in education, though they do not in Laurillard's view offer a strong teaching facility. There is also a very high risk of novices becoming lost in such systems. Hypertext programs may have value in highlighting students' misconception and in formative and summative testing of conceptual understanding, but it is as multimedia where their main potential rests. These may offer scope for individualised learning, provided that they are not only scaffolded, but also sufficiently interactive with the provision of suitable feedback. If the problems associated with navigation through such systems can be eliminated so that tutorial-type programs can be created in a flexible way depending on students' needs, it is possible that considerable intellectual gains could be made when using them.

The question, then, is how to support these different systems in the classroom so that they may be fully incorporated into teaching, improving conceptual understanding and problem solving abilities. Different psychological theories in the field of education have suggested alternative, though occasionally similar, approaches to learning, so to what extent can the different generic tools be regarded as following one approach as opposed to another? There are very distinct differences between say the behaviourist and constructivist approaches and between constructivism per se and social constructivism, which have offered specific insights into the learning process, as discussed in Section 2.2. An analysis from this perspective has merit, since it helps to

inform during the initial review stage of software analysis where the particular strengths and weakness of each piece lay.

2.4 Psychology and instructional design

2.4.1 Introduction

Laurillard has been frequently quoted as a guide to the benefits, in terms of interactivity, adaptability and so on, of these different systems. However, there is another, equally important aspect to consider that can provide insights into the design of and interaction with computer systems, which is the psychological perspective. Aspects of certain learning theories are either made explicit or are implicit in the design of software materials. This next section considers particularly constructivist and social constructivist theories with regard to generic computer tools.

2.4.2 Behaviourist and cognitive traditions

From the behaviourist point of view, knowledge is viewed as given and the teacher is the final authority in respect of what is known. A type of software to which this model might apply is the tutorial program, whose mode of teaching has been called computer-assisted instruction. Here instruction is expected to stand-alone: the student should be able to learn the topic without any help or other materials outside the courseware.

From the cognitivist perspective comes the Information Processing Tradition. Here knowledge acquisition is a mental activity and thus contrasts with the behaviourists' view, where exploration of cerebral processing was explicitly taboo. The development of computers with a strict input – processing – output architecture ties in well with the cognitivists' view and therefore this approach

prescribes learning events, which are analogous to the working of a computer. However, the essential element missing here is one absolutely essential in the learning process, which is a sound pedagogical base, arising out of a theory of learning.

2.4.3 Constructivist approach

Another important contribution as to how children learn can be considered under the general term constructivism, and the types of programs linked to this tradition are quite different from those connected with behaviourism and cognitivism. It differs from the aforementioned theories of learning in that it is relativistic: learners are seen as building personal interpretations of the world based on experiences and interactions, and may create novel and situation-specific understandings by assembling knowledge from diverse sources appropriate to the problem in hand. Above all cognitive conflict should be involved. From this perspective, the prescriptive principles should involve both discovery and cognitive conflict. The best programs that best approach these flexible-learning strategies are simulations and hypertext.

Each of the paradigms mentioned previously are useful in the design of software, but are only suitable if children learn in the ways prescribed. Certainly programmed instruction leads to learning, but possibly not to conceptual understanding as previously argued or to the ability to solve problems; the same might be said for learning within the cognitivist tradition, although a degree of reflection is required. Constructivism, with its open-ended approach may not be a sound basis for design either, unless appropriately scaffolded.

There is, therefore, potentially a significant problem in the design of educational material in the field of computing, especially since much of the research has not shown substantial gains in conceptual understanding or problem solving skills when computers are employed in learning. There are, however, some notable exceptions, which are cited elsewhere in this chapter. The problems may stem from the research methodology employed or it may well be that either the software or the way it is used may be fundamentally flawed. Certainly Whitelock (1999, p. 13) considers that *'cognitive science has not moved the field (of learning with computers) forward conceptually as predicted and neither has it affected the practice of designers and evaluators working at the sharp end of the software production business'*.

2.4.4 Social constructivist approach

Many researchers in the recent past have called for a more collaborative approach to learning. This is an element that has not been touched on so far but, in conjunction with computing, it may offer a new approach to learning that will enhance students' conceptual understanding and reasoning skills. It is an important avenue for research because:

- cognitive science is not moving the field of learning with computers forward;
- learning that takes place as a collaborative/co-operative venture is firmly rooted in current psychology be it social constructivism or phenomenography;
- opportunities for meaningful discourse with computers at the present time are limited.

As previously asserted the knowledge of science teaching and learning is limited but, if an intelligent tutoring system is considered to be the most effective means of learning with all that implies from conceptual understanding to problem solving, such knowledge is a prerequisite for the design of such a system. Additionally, for such a system to work effectively, it needs to be able to process natural language. Since these (and probably other) features are not forthcoming other avenues of enhancing student performance need to be investigated. These new routes require new approaches to research and analysis, which are certainly different from those used in traditional psychology.

Collaboration, context, the social setting and related factors have been recognised by psychologists as important in the learning process, but have largely been ignored in the context of computer learning. Vygotsky from the historico-cultural perspective recognised collaboration as being the key to understanding; it is the central issue. The Vygotskian perspective has been outlined earlier, but he was concerned about the social construction of knowledge, the dynamics of the learning process and the role of language, not the destination so much, but rather how the child reaches a certain goal. This is an active process, involving mediation with others.

Many authors have written in support of the computer as a mediational tool in a collaborative framework. Indeed, throughout the 1990's a number of articles appeared calling for computer based interactions, and others were empirical studies on collaboration, which at first focused on establishing parameters for effective collaboration, but more recently looked at the talk involved during

collaboration and in the joint activity when working together. Cumming (1993) proposed that intelligent educational systems should be developed by adding a module to support Discussion Level interaction with the learner. He suggests that too much of the Interactive Tutoring Systems (ITS) research field has been driven by technical possibilities, and fascination with programming and knowledge presentation techniques, rather than on learning issues. McKendree et al. (1998) reported on the Vicarious Learner Project, which investigated the fundamental role of dialogue for learning. They make the point that learning comes through dialogue, but it is being squeezed out of the formal educational system, particularly in higher education, because of the growing emphasis on the use of educational technology, which does not encourage it. They emphasise that in an educational dialogue there is often a divergence of conceptual understanding, leading to cognitive conflict. Frequently a new understanding arises, not by learning a new fact which was not there before, but by juxtaposing ideas in a novel way, realising a consequence which had not before been considered.

Pilkington (1998, p. 308) asks the question, '*Do students always interact with computers reflectively on tasks and improve qualitative reasoning?*'. If high quality educational interactions with computers are to take place, then it is necessary to understand the situations in which particular dialogue forms are effective and to find ways of modelling these within the software. She found that experimenter-student dialogue was more likely to prompt reflection and reasoning activities than student-student dialogue. Ravenscroft (2000, p. 241), investigated '*student-tutor-system interactions in ways which inform the development and use of virtual systems and environments, where*

the aim is to develop meaning and promote understanding through a guided pedagogy' and Ravenscroft & Matheson (2002, p. 93) report on dialogue games for collaborative e-learning for the purpose of designing cognitive tools that can be designed to *'stimulate, support and mediate discourse processes that lead to conceptual development'*. Their research suggests that collaborative and argumentative dialogue improve students' knowledge and conceptual understanding. White & Fredericksen's (2005) work on providing students with varying roles in the collaborative context shows that collaborative skills may be developed in students resulting in the improvement of *'their metacognitive theories and capabilities'* (p. 221).

The recurring observation from natural classroom tasks is that boys see the computer as being in their domain, but classroom experiments show that girls perform as well as, if not better than boys. Reported research in Underwood & Underwood (1999) suggests that when boys and girls are paired together girls perform less well. Howe & Tolmie (1999) indicate that research shows that there are benefits in collaborative work with computers where the conceptions of the participants differ. Whitelock et al. (1992) have shown that dominance, as well as students' views on topics are important factors in group work performance. Where one of the participants is dominant, performance is not so great, whereas if they have contrasting points of view, there are enhanced results.

2.4.5 Conclusions

Adaptive media may be behaviourist or cognitive in approach, and students using them, may arrive at a re-description of the material. Specific routes may

be followed, without requiring reflection and interaction by the learner, so that a pre-determined outcome is realised, which allows the student to imitate the program, since the knowledge received is rather like bits of information, but is not conceptual gain at all. On the other hand generic tools, which provide potential for a more open ended result, such as some simulation software and hypermedia are potentially relativistic in outcome, and may be considered constructivist. However, they provide opportunities for personal involvement, which absolutist systems, such as tutorial programs, may not, but they are frequently difficult to navigate through. They may provide opportunities for interaction, such as feedback, though it is suggested that hypermedia programs do not. Research strongly supports the view that whatever system is operated student gains are relatively modest, which may suggest that learning with:

- computers is not effective;
- certain types of program is not effective;
- computers requires the addition of other dimensions; such as scaffolding by and discourse with a knowledgeable other.

The third of these requires considerable additional research data, though a start has been made. Recent work does suggest that collaborative endeavour does enhance learning, but much more research work needs to be undertaken in this area.

Another possibility is that the research methodologies used to determine educational gains when computers are used are inadequate in discovering the educational changes that take place. This is discussed in Chapter 4.

Chapter 3 Learning about photosynthesis

3.1 Introduction

Students from a number of different backgrounds, having been exposed to a variety of experiences, will inevitably possess different ideas about studies, not least about science and in particular about photosynthesis. It is the role of the teacher to develop in the student an understanding that is both personal and one that is constructed around a shared body of culturally accepted knowledge.

In order to build this shared understanding, it is necessary for the teacher to develop a picture of a student's ideas at the outset, as well as during the learning process itself. In order, therefore to build a teaching strategy it is necessary to take account of a student's:

- initial conceptual grasp, major errors and misconceptions;
- and developing conceptual understanding as the learning process proceeds.

Prior knowledge is considered an important determinant for future learning. Some authors in the twentieth century, such as de Jong & van Joolingen (1998) and Glaser et al. (1992) refer to the value of students possessing sufficient expertise in certain domains of knowledge at the outset for successful completion of simulation exercises. More recently Day (2000), Shapiro (2004) Ertl & Mandl (2006) and Kerr et al. (2006) refer to the significance of prior knowledge for individual learning (Shapiro 2004), for learning in a collaborative environment (Day 2000, Ertl & Mandl 2006) and from the constructivist perspective (Kerr 2006). Many empirical studies, such as those of O'Donnell & Dansereau (2000), Kalyuga et al. (2001), Shapiro

(2004) and Yenilmez et al. (2006) suggest that this initial knowledge is a factor in determining conceptual development. Indeed in Shapiro's study, prior knowledge accounted for a large portion of the subjects' post-test performance. This prior knowledge is referred to within the literature in a variety of ways, for example, as preconceptions, alternative conceptions and naïve ideas, but these may be corralled under the generic term 'misconceptions' (Smith et al. 1993).

The importance of misconceptions in detracting from the learning process is confirmed by the fact that there is a body of written work, known as misconceptions, which is vast, and in the late 1990s (Pfundt & Duit 1998) stood at 4,500 entries, including many on photosynthesis, where Mintzes & Wandersee (1998) acknowledge that students find difficulty with a wide range of concepts. There is much research suggesting that misconceptions must be addressed before instruction takes place (Driver 1988, Duit 1991, von Glaserfeld 1992, Shuell et al., 1992, Laurillard 1993, Hennessy et al. 1995, Taber 2000, Grayson et al. 2001, Palmer 2001, Chi 2005) and some, such as Tiberghien (1985), which monitor children's scientific conceptual understanding during instruction. There is one seminal study by Driver (1998) that suggests a teaching strategy, whereby conceptual understanding may be enhanced when the prior conceptions of the student are known by the teacher, which includes:

- broadening the range of application of a conception, so that students' prior conceptions can be used as a resource that can be extended;
- differentiation of a concept (since students may only have a global, some might say intuitive, conception that is ill-defined because particular

experiences, be they in the laboratory, in the classroom or at the computer, have not occurred) to help them differentiate their ideas;

- constructing alternative concepts (since students' naïve concepts cannot be accommodated in new, formal scientific ones) by discussion with teachers, and evaluation of the developing conceptual model by contrasting it with naïve ideas.

Nevertheless these misconceptions are often stable and resistant to instruction (Anderson & Smith 1987) and in the physical sciences, conceptual understanding is problematic, since the ideas are often counterintuitive, though sometimes perhaps relatively easily resolved (Whitelock 1991, Palmer et al. 1997) if misconceptions are as Niaz (2001) describes 'soft core'. However, in biology many of the intellectual hurdles can only be overcome by integrating knowledge from several sources (Azevedo 2005). In the field of biology also, photosynthesis is an especially difficult topic for students at any level, since plants are involved (being more unattractive to study than animals), theory is so divorced from perceptions, knowledge of organic chemistry is required, energy transduction needs to be understood and the raw materials look inert.

School pupils are not generally interested in plant biology, since plants appear to be inactive entities that do not respond in the way that animals do. Photosynthesis itself seems to be a most unlikely process, since there is so very little about it that can be directly observed, even at the most elementary level, especially with regard to the reactants, carbon dioxide and water. The products, organic molecules, like carbohydrates, and the gas, oxygen, are more likely to have an impact on children's understanding of the process, but

there is both considerable delay in product formation, and intellectual problems that relate to the inferences to be made from any diagnostic tests. Indeed, as Barker & Carr (1989 (a)) explain, pupils do not see the whole process as being about producing a solid carbohydrate product, and as Stavy et al. (1987) acknowledge, students find photosynthesis hard to grasp. Unfortunately, everything that pupils observe about the process is one or more stages from the site of the process itself, that is photosynthetic cells.

It is regrettable that students find photosynthesis such a difficult topic, because it is the basic mechanism involved in the maintenance of the biosphere.

3.2 Conceptual difficulties with photosynthesis

As has been described, photosynthesis is a complex process, much divorced from the final products of carbohydrate and oxygen, which requires a sound knowledge and understanding of many aspects of science, not just those of biology, but of physics and chemistry, too. At the sixth form level, it is necessary to understand complex biological and physical principles. From the biological perspective it is necessary to know not just plant structure at the anatomical level, but also leaf structure at the levels of resolution possible through the use of the light and electron microscopes, as well as to comprehend models of the organisation of cell membranes. Physical principles that need to be understood are those of diffusion, light energy and its transduction into chemical energy, which is photochemistry, together with more familiar chemical principles, including catalysis and chemical reactions. For many students, taking biology at an advanced level, these physico-

chemical principles are problematic (Ross et al. 2006), as are those involving the establishment of a pH gradient across the thylakoid membranes. In addition, these complex structures and processes need to be inter-related, so that: a comprehensive understanding of photosynthesis can be embraced so that the immense power that plants possess in converting sunlight energy into adenosine triphosphate (ATP) can be better perceived.

With such an immensely difficult process, sixth form students after being taught about photosynthesis are going to possess a variety of misconceptions about it and even at an earlier, more elementary level may possess naive ideas and incorrect prior conceptions, which may affect future learning. As Driver et al. (1985 p. 199) recognise *'it is [in curriculum planning]...necessary not only to consider the structure of the subject but also to take into account the learner's ideas. This may mean revising what we consider the starting points in our teaching – the ideas that we can consider pupils have available to them.'* What are these naïve ideas and misconceptions, and are there any generic ones? The next section looks at various studies that have been undertaken to discover what these misconceptions are, how they may be determined as well as at some methodologies that may assist in removing them that are possibly relevant to the current research.

3.3 Misconceptions and conceptual understanding of photosynthesis

As noted in the introduction, there are a large number of research documents on the topic of misconceptions, mainly at pre-sixteen levels, reflecting the importance that is attached to it from the pedagogical point of view. However,

there are relatively few on the methodologies for removing them or on students' overall understanding of the photosynthetic process. In the sciences and mathematics in particular there is a wealth of research on the topic of misconceptions (Smith et al. 1993). These authors are concerned that '*misconceptions interfere with learning, [about their] need to be replaced [and that] instruction should confront misconceptions*' (pp. 121-122). They also point out the importance of discovering students' ideas, not just by deciding whether their answers are correct or not, but by analysing detailed responses. Moreover they advocate this procedure as a means to discover where gaps occur in their grasp of a given scientific topic. One such method is by using concept maps, which have been used to develop insights into biological topics, such as respiration, by Songer & Mintzes (1994) and supported by Kinchin (2000 (a)) not only in assisting students to learn about photosynthesis, but also to provide their mentors with an understanding of their students' misconceptions. Another approach is that of categorising students' potential conceptual difficulties in new areas of study as demonstrated by Grayson (2001) with regard to oxidative phosphorylation.

There is considerable research into students' ideas on photosynthesis in the secondary and tertiary sectors of education, which is reviewed in this section. There is evidence of world wide interest in the subject for the reasons cited previously, with reports, included in this review, of research papers from, for example, the U.S.A., Australia, Israel, Hong Kong, New Zealand, Spain and the U.K.

What common misconceptions do students hold about photosynthesis? Some research emanating from these countries report student misconceptions, particularly from the work of Wandersee (1983), Haslam & Treagust (1987) Cho (1988) and Kinchin (2000(b)). Other authors report specifically on confusion that students have between respiration and photosynthesis, particularly Simpson & Arnold (1982), Stavy et al. (1987), Anderson et al. (1990), Amir & Tamir (1995), Haslam & Treagust (1987), Lenton & Turner (1999) and Canal (1999).

The methodologies for determining misconceptions and understanding are the specific subjects of a number of authors, such as Yip (1988) and Anderson et al. (1990), but are also developed by others, such as Wandersee (1983), Haslam & Treagust (1987) and Amir & Tamir (1995). Haslam & Treagust (1987) outline a test, which they describe as a two-tier test. Yip (1988) provides a critique of the various types of test that have been used, suggesting a new instrument consisting of statements concerned with biological topics about which respondents' comment. Anderson et al. (1990) develop the concept of the 'goal conception' in order to identify a student's understanding. Amir & Tamir (1995) use a Proposition Generating Task (PGT), which is based on the principal of concept mapping. Wandersee (1983) employs a diagnostic tool called the Photosynthetic Concept Test (PCT), which consists of twelve tasks, each involving an experiment, a phenomenon, or a situation that calls for a student response. Finally, Cho (1988) uses a modified form of Wandersee's PCT and a Piagetian Logical Reasoning Test to investigate the relationship between conceptual understanding of photosynthesis and reasoning ability.

A number of researchers have taken a particular theoretical slant to their investigations. Cho's work is based on Piaget's epistemology; Wandersee takes an Ausubelian perspective on concept development, others, such as Driver & Bell (1986), fit into the constructivist (though not explicitly Piagetian) framework. Lumpe & Staver (1995) take a Vygotskian perspective on methodologies that may reduce misunderstandings in photosynthesis.

Some researchers have reported on specific teaching methods that have attempted to improve student grasp of photosynthesis. However, there are in fact relatively few reports in the literature, which include those of Barker & Carr (1989 (a) and (b)), Eisen & Stavy (1993), Lumpe & Staver (1995) and Ross et al. 2006).

For clarity, this review of misconceptions research is split into three broad themes. First, the methodologies that have been used for determining misconceptions in photosynthesis, second the particular psychological slant that various researchers have taken and finally the pedagogical strategies that have been adopted in the classroom. In each of them the research findings are summarised.

3.3.1 Research findings and methodologies

In a study by Haslam & Treagust (1987) secondary students' misconceptions of photosynthesis and respiration were investigated using an adaptation of the multiple-choice test, the two-tier multiple-choice instrument. The multiple-choice methodology has a long tradition, and has been used by many other researchers in the field (Doran 1972, Linke & Venz 1978 and 1979, Halloun &

Hestenes 1985 and, more recently, by Marmaroti & Galanoupolou (2006), though as Proposition Generating Tasks (PGTs).

However, the two-tier multiple-choice test first described by Treagust & Haslam (1986) has an advantage over a straightforward multiple-choice test (mct), because in addition to a mct response, students are expected to select a reason for their answer from a number of choices. It is suggested that a much greater insight is therefore provided as to the students' understanding by this approach, though some, such as Griffard & Wandersee (2001), have voiced concerns about its validity. A number of misconceptions were identified in relation to photosynthesis, most particularly that it is an energy providing process but, as Bell (1985) reported, students often lack a coherent understanding of the various physiological and bio-chemical process, such as breathing and respiration, that occur in plants. Canal (1999) in his review paper, suggests, together with Simpson & Arnold (1982) and Stavy et al. (1987), that the nature of photosynthesis as the reverse of respiration (i.e. inverse respiration) is promoted by the teaching that occurs at the primary and secondary levels.

Yip (1988) studied misconceptions, using novice teachers, in various areas of biology including photosynthesis emphasises the fact that wrong ideas, which are firmly held, are an impediment to future understanding and learning. He considers different types of 'test' that may illicit student misconceptions. He looked at the pros and cons of various techniques, which may uncover just how much students do know about a topic, such as photosynthesis. For example, multiple-choice items, which are easy to administer, *'often fail to*

explore the reasoning processes and sources of conceptual problems of the subjects` (p. 463). In contrast, written tests are more embedded in providing insights, but it is difficult to quantify results or to eliminate the subjectivity of the interviewer. Clinical interviews are valued because they `can probe into students mental processes more specifically, but they are time consuming to administer and require expert skills if they are to be conducted successfully` (p. 463).

Yip, therefore, proposes a new instrument for studying misconceptions. Consisting of questions, each one being made up of short statements on a particular biological concept. Respondents, teachers in this case, are asked to indicate whether such statements are *`correct, partially correct or incorrect, (to) underline parts that they consider to be incorrect and provide justifications for their answers`* (p. 463).

Amir and Tamir (1995) also review the various methodologies for determining conceptual understanding, suggesting the strengths and limitations of each one. They outline a new procedure, called the Proposition Generating Task (PGT) as an effective alternative tool to concept mapping. They consider that this is the simplest form of concept map, and its strength when compared to Yip's method is that it shows relationships between concepts and, in their particular study, between photosynthesis and respiration. Year 11 and 12 students were pre-tested before the study and post-tested afterwards, and their statements categorised, with the *`highest`* category being the *`goal conception`* as outlined by Anderson et al. (1990) (see below). In this study the goal conceptions were complementary statements in relation to

photosynthesis and respiration. Students often offered the view that photosynthesis and respiration are opposite processes, which is too simplistic. Marmaroti & Galanopoulou (2006) propose a similar approach, which was applied to students in 'middle secondary schools', to a number of topics on photosynthesis. Their findings suggest that students at this age experience misconceptions relating to the involvement of chlorophyll in the process and to the transformation of matter and of energy and possess naïve ideas about the source of a plant's food.

Anderson et al. in their study of the effects of instruction on conceptual understanding of respiration and photosynthesis introduced the idea of '*goal conception*' (p. 771) in order to provide a focus when analysing students' understanding of a variety of plant processes. In this study of university students, all of them took biology, as a subsidiary subject. The study used written tests and multiple-choice items to register students' understanding of photosynthesis and respiration before and after instruction. In this study also, students taking the pre-test could not provide acceptable definitions of respiration, photosynthesis or food. Following a course of instruction, these concepts in relation to green plants were resistant to change, with a large minority of students failing to reach the goal concept in relation to food production by plants and the energy sources of both plants and animal.

Wandersee (1983) investigated misconceptions in photosynthesis using a diagnostic tool called Photosynthetic Concept Test (PCT), involving students in Years 5, 8 and 11, from junior high school to college. The test consists of 12 tasks, which are in many ways like the PGT, in topic specific areas where

he, Wandersee, considered that students would require sound sub-concepts in order to grasp an overall understanding of photosynthesis. Questions were devised in order to discover student misconceptions in four broad areas:

- the basic function of soil in plant growth and photosynthesis;
- the basic role of photosynthesis in the carbon cycle;
- the basic roles of the leaf and light energy;
- the primary source of food in green plants.

In this snapshot investigation, Wandersee found that students' concepts of photosynthesis did change as they progressed through the educational system. However, students showed the least improvement in the following concepts, which may be resistant to change:

- the role of water in photosynthesis;
- the role of chloroplasts;
- the importance of carbon dioxide as the main source of 'raw material' for photosynthesis;
- the 'product' of photosynthesis, carbohydrates.

He identifies 31 naïve ideas and misconceptions, which may be grouped into features that might be best described as to do with concepts about the structure of leaves, the biochemistry of the process, biophysics, energy in relation to the soil and a set that is simply designated 'miscellaneous ideas', because they do not fit into a common group (Table 3.1).

Categories of misconception	Statement
Structure and function of leaves and stems	<ol style="list-style-type: none"> 1. Rain goes in the holes of leaves 2. The leaf's main job is to capture the sun's warmth 3. The leaf's main job is to capture the rain and water vapour in the air 4. Leaves drink in the dew 5. Phloem carries water and food from the soil to the top of the plant 6. Water vapour moves into a leaf during photosynthesis
Biochemistry	<ol style="list-style-type: none"> 1. Plants give off mainly carbon dioxide 2. Plants take oxygen out of the air during photosynthesis 3. The chemical that absorbs sunlight in leaves is 'chlorine', or chloroform, or chloraseptic 4. The soil supplies most of the 'raw materials' for photosynthesis 5. Food cannot be made out of the air 6. Plants change water into sugar 7. Plants produce protein in photosynthesis
Energy and soil function	<ol style="list-style-type: none"> 1. The soil loses weight as plants grow in it 2. The soil is the plant's food 3. Plants eat minerals 4. Plants get protein from the soil 5. Plants feed on water 6. Plants get vitamins from the soil 7. Plants get their food from the roots and then store it in their leaves* 8. People put food (fertiliser) in the soil for plant's to eat 9. Roots absorb the soil 10. Soil; has nothing to do with plant growth
Biophysics	<ol style="list-style-type: none"> 1. Plants convert energy from the sun directly into matter
Miscellaneous	<p>Plant's grow to a giant size in the dark Chlorophyll is the plant's blood Leaves change colour because they cannot breathe Trees sleep in the winter Chlorophyll is no longer available in the air in the fall so the leaf cannot get food In the fall, chlorophyll cannot get into the leaves from the trunk any longer... a little valve in the leaf stem closes There are things floating in the air for the plants to live on</p>

Table 3.1 Categories of misconceptions (after Wandersee)

Other studies, some before and some after Wandersee, tell a similar story of a woeful misunderstanding of what photosynthesis actually is. Cho (1988) undertook a study of fifth and eighth grade Korean students, using a model of photosynthesis as a platform on which to base his photosynthetic questions. He used a modified form of Wandersee's PCT, and a Piagetian Logical Reasoning Test (PLRT). Cho concluded from the students' responses that there were persistent misconceptions, which concerned, making food, the role

of light, root function, leaves, photosynthetic products and the elements required for photosynthesis, specifically the roles of iron and magnesium. Stavy et al. (1987) report the misconceptions held by students, aged 13 -15 in a comprehensive school, determined through the use of interviews. They highlight misconceptions about the chemistry and the chemical composition of the body, about the nature of gases, and about photosynthesis and respiration. On these last two topics, as reported elsewhere in this review, many students thought of photosynthesis as a type of respiration or as a process of gas exchange and *students know many bits and pieces of information about photosynthesis, but they lack a meaningful and general view of it* (Cho 1998, p.113), which echo's Bell's (1985) view.

All these studies reveal a large number of misconceptions that are possessed, not only by school students, but also by undergraduate ones, too. Many of these misconceptions, as has been reported, are persistent, particularly those that relate to gas exchange, the source of energy for, and its role, in photosynthesis, the role of nutrients in the soil, the organic products that are made from the first organic product, glucose, such as cellulose, many of which may hamper further understanding. Kinchin (2000 (b)) when reviewing previous research has reduced the problems inherent in an understanding of photosynthesis at the pre- sixth form school level to 8 statements together with 2 longer descriptions under each stating alternate and opposed views. These statements are:

1. Gardeners can give plants food (in the form of fertilisers);
2. Photosynthesis produces energy (in the form of starch);
3. Photosynthesis converts sunlight into starch;
4. Plants get some energy from the soil;

5. The hard material in plants (e.g. wood) is made of minerals taken from the soil;
6. Plants need energy to grow;
7. Photosynthesis breathes out oxygen during the day and carbon dioxide at night;
8. Carbohydrates are made by plants so they can be stored.

3.3.2 Psychological theories and research methodologies adopted

Many of the pieces of research previously briefly described have either been ascribed to a specific psychological tradition, or have strongly suggested that this was so. Being such an intractable problem, with so many misconceptions attached to it, different researchers have returned to it, not only to determine what these misconceptions actually are, but also to suggest methodologies that might best eradicate these. Frequently these methodologies have taken a specific psychological slant.

Cho's work was in part developed from the Piagetian tradition of genetic epistemology which showed that there was no significant difference between his Piagetian Logical Reasoning Test and the Photosynthetic Concept Test. This enabled him to suggest that topics should be only be taught at particular points appropriate to students' cognitive development.

The researches of Barker & Carr (1989) (a) and (b), Driver & Bell (1986), Haslam & Treagust (1987) have all been previously noted. They are all, however, based on the constructivist tradition, although Barker and Carr borrow ideas from the Theory of Subsumption (Ausubel 1963). The researches of Simpson & Arnold (1982), Wandersee (1983) MacGuire &

Johnstone (1987), are explicitly Ausubelian in their approach, and that of Amir & Tamir (1995) is implicitly so.

Only one study so far published is grounded in the ideas developed by Vygotsky, namely that of Lumpe & Staver (1995), though Hodson & Hodson (1998) have outlined the Vygotskian tradition position and called for more group work. Lumpe & Staver outline the different educational psychologists' perspectives, including those of Piaget, Ausubel (1963) and Vygotsky. Whilst cognitive structures are important in conceptual development, as are the conceptions or even misconceptions that students bring into the classroom. Other important factors on student progress, such as social factors are important, too. Lumpe and Staver outline ideas involved with co-operative learning, such as peer tutoring, co-operative learning and peer collaboration. They outline the role of Piaget in this respect, where he contended that peer interaction could be a catalyst for cognitive conflict, and therefore conceptual change. Vygotsky is brought into play with their use of his term 'zone of proximal development', but his seminal role in advocating the use of an 'expert' other is underplayed. Sullivan (1953) is also quoted in relation to his co-constructivist theory and peer collaboration in promoting conceptual change.

The work of Simpson & Arnold (1982) on pre-requisite concepts is outlined here, because it acknowledges that there are rival claims of various psychologies to present the best route through which learning occurs. The research nevertheless took on a particularly Ausubelian stance, and considered four concept areas that required to be developed in order to

understand photosynthesis. These are the concepts of living things, food, gases and energy. The students, who were of primary age, all showed deficiencies in their understanding of these basic concepts. How then are pupils expected to improve their ideas? They suggest that Gagne (1977), and his hierarchical theories of learning are more relevant to Physics and Chemistry, but not to photosynthesis, which can neither be taught through a progression of skills, nor via a best route.

Shayer (1974) has suggested that an understanding of photosynthesis on past Nuffield O-level courses requires a capacity to operate at a Piagetian level of formal thought, which is not attained by the majority of 16-year-olds. Nevertheless, Simpson & Arnold (1982) draw a conclusion from their work, which contrasts with that of Cho (1988). This is that *'until it can be demonstrated that an understanding of these processes [photosynthesis, respiration, genetics and evolution] is precluded even when stable pre-requisite concepts are known by the learner, the conclusion that these topics are intrinsically too difficult should not be drawn'* (Simpson & Arnold 1982, p. 71). Novak (1978, p. 26) agrees that *'if most people, children or adults, can evidence highly formal and abstract thinking when they have acquired a sufficiently well developed framework of concepts relevant to the tasks, then we could be optimistic regarding the importance and promise of well designed educational experiences. This presents education with an incredible challenge'*. What then is the role of the pedagogue in enabling students to develop a greater understanding of photosynthesis? The next section looks at a number of studies that have attempted to answer this question.

3.3.3 Pedagogical strategies for teaching photosynthesis

Many misconceptions are persistent and resistant to instruction in a variety of subject areas, but not all misconceptions are stable and resistant to change (Niaz 1991, Palmer 1991, Smith et al. 1993, Chi 2005). In addition, in science and mathematics learning there has been little emphasis on the type research that describes the kind of instruction that successfully promotes learning. It is, therefore, not surprising that there are relatively few reports on teaching strategies that are found to be effective in addressing the question of misconceptions in photosynthesis.

Eisen & Stavy (1993) studied 14- to 15-year-old students who were taught photosynthesis according to a science curriculum based on research on misconceptions and compared to those who had not. The two groups were given the Classroom Test of Formal Operations (Lawson 1978) and no significant differences were found between the students' Piagetian levels. There were, however, differences between the two groups in understanding of ecosystems, chemistry and respiration, and the results for ecosystems and respiration were significant. The teaching strategy adopted with 14-15-year-olds in the experimental group had the expressed desire to remove past misconceptions and to organise the content in such a way as to change pre-existing misconceptions and to prevent the formation of new ones. The researchers attempted to remove these misconceptions by considering stories from the history of science, and to ease them into the chemical aspects of the subject by integrating the teaching of chemistry with biology.

Barker & Carr (1989 (a) and (b)) undertook a study in which the teaching package used was based on the Generative Learning Model devised by Osborne & Wittrock (1985). The study was undertaken on 14-year-olds by using a teaching package 'Where does the wood come from?' The outcome of the teaching package was evaluated from five research strategies, including observations and recording of classroom activities, interviews and written responses. The generative learning model has eight attributes and the teaching package was intended to address each of them. Importantly the research incorporates a number of important pedagogical attributes, such as students' pre-existing (naïve) ideas with links to more scientific ones, so that the student constructs new meaning and teachers ascertain students' ideas prior to instruction, facilitate the exchange of views, and challenge students to compare ideas. Learning did occur during these studies, but the length of exposure of these students to the topic – a fortnight – in twelve hour-long lessons is not something that could be anticipated in most teaching situations. The conclusions were not particularly comprehensive, though most students were able to express the 'scientist's' view about 'plants and the gases in the air' and could write a paragraph in answer to the question, 'What is photosynthesis?' from a scientist's perspective.

The work of Lumpe & Staver (1995) is reviewed at some length, since there are some implications for the present study. They attempted quite explicitly to show that students working in a collaborative atmosphere understood more about photosynthesis than those who did not; in other words their concepts of the process was more closely allied to the scientists' notions of the process, as did Barker & Carr (1989 (a) and (b)). High school students were randomly

assigned into treatment (peer collaborative) and control (individual learner) groups.

During the research period, the sessions were audiotaped. The tasks that the students were set were adapted from other research programmes, such as those of Cho (1988) and Wandersee (1983), and the students were subjected to four separate and formal sessions lasting about 30 minutes, as well as 3-4 weeks to care for their live plants as part of the experiments they designed and conducted in the sessions.

Their methods of assessment require detailed comment, since they draw on a battery of techniques that have implications for the present study. In addition, their conclusions and inferences are worth considering in some depth, too, particularly in relation to misconceptions.

First, the PCT test was used in preference to the multiple-choice test (mct), since it is open-ended, giving greater insights into students' knowledge and understanding. The items of the PCT were constructed by analysing students' misconceptions, both from clinical interviews and from proposition-type tasks generated from teachers' guides to textbooks. These misconceptions were categorised, and 10 goal conceptions formulated, which are illustrated in Table 3.2.

1a	Plants make their own food internally
1b	The food that plants make internally is the plant's only source of food
2	Food made by the plants is matter that they can use as a source of energy
3	Food supplies the energy that plants need for life processes
4	Water and carbon dioxide are changed into another form of matter as a result of a chemical reaction
5a	Water and carbon dioxide travel to leaves where they are involved in the making of food
6b	Food travels from where it is made to all parts of the plant
7	During photosynthesis, energy from the sun is changed into energy in the form of food (glucose, sugar, starch)
8	The food that plants make is their only source of energy
9	Animals depend on plants for food and oxygen. Only green plants can make the energy containing food that all animals need

Table 3.2 Goal conceptions of the PCT (adapted from the Institute of Research in Teaching 1985, pp. 1-6 taken from Lumpe and Staver 1995)

The PCT was administered as a pre- and post-test on individual students, and the students' responses codified in order to permit statistical analysis. In addition, it was administered to the groups as a whole, as a contextualised assessment before the individualised assessment, which was undertaken some time after the groups disbanded. As well as the collection of this quantifiable data, qualitative information was sought from student-student interaction, student-teacher interaction, open-ended questions and summaries.

In order to analyse the quantitative results, it was necessary not only to codify them, but also to justify the system used. The results from the students' statements were categorised using a system similar to that of Simpson & Marek (1988) into '*sound understanding* [all elements of the goal concept], *partial understanding* [some elements of the goal concept], *partial understanding with misunderstanding* [part or all aspects of the goal concept, with some misunderstanding], *complete misunderstanding* and *no response*.

The major findings of this research are summarised below. Students working in groups outperformed students working alone. With regard to prior conceptual knowledge, the effect of this has already been reported (Smith et al. 1993), but this investigation also, by reporting on students' comments during their discourse, shows that certain views, such that plants obtain food from external sources is extremely difficult to change into the acceptable scientific view, which is that plant food is made internally. This has been reported previously (Canal 1999), but it seems that short, collaborative treatment does not remove strongly held informal, spontaneous concepts, which have taken a lifetime to construct (Pines & West 1986). Nevertheless students with misconceptions at the outset were, as the discourse progressed, able to minimise the impact of these on the group discussion, though they did affect their ability to progress. Additionally, from this study, it appears quite possible for students working in groups to develop sound, scientific concepts related to the PCT, when tested alone, but group members could only do so on some of these concepts when tested alone, suggesting that *'the synergy present during group work does not necessarily carry over to the post-test assessment'* (Lumpe & Staver 1995, p. 90).

Those concepts that students retained were those that had been discussed most during the interactions. The interactions themselves that promoted most conceptual change were placed in two groups, called *consonant* and *dissonant*, which are shown in Table 3.3.

Consonant	Dissonant
Providing additional help Requesting help from others Supporting another's good ideas Summarising ideas Requesting support Explicit agreement Implicit agreement Finishing another's sentence Expressing pleasure of constructed ideas (reflexivity)	Complex argument structures Not recognising another's poor idea Criticism of one's own ideas Criticism of another's idea

Table 3.3 Types of peer interaction enhancing concept development

This study shows clearly that collaborative activity has a positive effect on conceptual understanding in photosynthesis. It also demonstrates the kinds of interactions, including Piagetian conflict resolution, that are most likely to prove successful, especially if they are employed frequently on any of the PCT areas. It also provides support to the Vygotskian perspective about collaboration, about the essential differences between everyday and scientific concepts (and the difficulty of bridging the gap between them during instruction), and about the zone of proximal development, where students gain from working in groups (in this case with individuals possessing different skills), but who cannot as yet make the equivalent gains when tested alone, after working in groups. One worker (Forman 1989) uses the term 'bidirectional zone' to explain the enhanced problem-solving ability of peer groups.

3.4 Conclusions

Students, it seems, hold considerable conceptual misunderstanding about the process of photosynthesis. The studies that have been discussed investigate the understanding of the individual elements of the process that might be expected of pre-sixth form students or of teachers who instruct them. A variety of assessment tools for discovering student knowledge about the

photosynthetic topic have been discussed, among them the PCT, PGT and the two-tier multiple choice test. They appear to show a large number of misconceptions. Wandersee (1983) listed 31 misconceived ideas, together with some that are resistant to change; Cho (1988) discovered 6, which were about the nature of plant food, the relevance of light, the function of roots, and leaves, the products and reactants of the process, which is incorporated into the sixth, which is that a whole range of chemicals, glucose, fat, nitrogen and protein are required for the process. Kinchin (2000 (b)) lists 8, which he considers are the most important in inhibiting the development of an understanding of photosynthesis.

There are only a handful of studies that investigate either the effect of a teaching strategy, or of a methodology on student misconceptions. Nevertheless the studies that are listed are encouraging in that they show student conceptual improvement.

Even so, we need to know more about what conceptions or misconceptions students hold relevant to the task, as well as methodologies that might enhance learning using prior knowledge of misconceptions. In addition, we need to develop new pedagogies to aid concept development and to raise the level of thought in our population of students. It may, then, be possible to raise the level of cognitive structure by both imaginative and appropriate teaching and learning strategies.

In order to gauge insights into A-level student understanding of the process of photosynthesis and to inform not only where students' difficulties with the process might be but also which misconceptions were held after a taught

course – both of basic (as outlined in the previous reports) and at a more sophisticated level) two pieces of fieldwork were undertaken: the first between October 1999 and February 2000 and the second in July 2000.

3.5 Fieldwork using A-level students

If pre-A level students, as the previous review suggests, carry misconceptions about photosynthesis, what ideas do sixth formers possess about the process and what do examiners require of them?*

The literature review has nothing to say on what misunderstanding sixth form students may possess about photosynthesis, though there are suggestions from research papers (Anderson et al. 1990, Boyes & Stanistreet 1991, Yip 1988) that undergraduates and student teachers lack an overall conceptual grasp (what might be called 'the big picture'). Anderson et al. (1990) found that university students could not give 'biologically acceptable' definitions of photosynthesis and respiration, and Boyes & Stanistreet (1991) discovered that energy relationships were much misunderstood, and first year undergraduates possessed persistent misconceptions, that included the naïve one that soil supplies food and energy for the plant. Yip (1988), studying misconceptions in novice teachers was struck by how firmly held wrong ideas were, and how resistant they were to change. In the first study, assistance was sought from, and agreed by, four English examination boards. It was conducted by employing students' answers in past examinations from papers that were held by AEB (Associated Examining Board)**, EDEXCEL, NEAB (Northern Examining and Assessment Board)** and OCR (Oxford and

* Appendix A carries a summary of photosynthesis

** Called AQA (Assessment and Qualifications Alliance)

Cambridge and RSA Examinations). In the second study, interviews were conducted with students at the end of their first year in the sixth form, having studied photosynthesis and taken a module examination, which included questions on that topic. In this first investigation, examining A-level answers, up to 30 students' papers were analysed for each question. Almost all the questions between 1996 and 1999 on photosynthesis from these boards were analysed using scripts retained for training purposes. Altogether 141 scripts were seen. Depending on the boards' system of retaining sample papers, as far as possible questions were sampled from the top, middle and lower ability ranges as determined by the grade obtained on the paper overall. For the most part, questions required detailed knowledge of events taking place within the chloroplasts, and therefore few insights could be gained about students' overall understanding of the photosynthetic process.

In the second study, this weakness was addressed, since it sought to search for elementary misconceptions. In addition, further clarification of students' misconceptions related to A-level concepts were investigated. The interviews were based on Kinchin's (2000) statements and on past A-level papers. Students all came from Thurleston High School, Ipswich. Four students were interviewed, who all had reached the end of their first year in the sixth form and had completed a course on photosynthesis.

An analysis of students' answers in the first study suggested that they held common misconceptions about:

- limiting factors and the rate of photosynthesis;
- the relationship between structure and function of chloroplasts;

- leaf structure and adaptations for photosynthesis;
- the absorption spectrum and chlorophyll pigments;
- activation of chlorophyll as a result of light absorption;
- energy: light, heat and electron activation;
- the links between the light-dependent and -independent stage;
- the role of ATP in energy transfer;
- ideas about reduction and oxidation;
- the role of reduced NADP in reduction;
- the nomenclature of biochemical compounds.

This study reveals that examiners set questions at A-level that expect students to possess considerable understanding of the highly detailed parts of photosynthesis, which is beyond that expected at GCSE. It also suggests that students do not know them very well. There is undoubtedly an assumption here that students do have an overall conceptual understanding of the process, and that they are not bringing misconceptions with them from their pre-A level studies. However, various studies (Anderson & Sheldon 1990, Boyes & Stanistreet 1991, Yip 1988) suggest that this may not be the case, since postgraduate and undergraduate students hold mistaken ideas and, frequently, at the most elementary levels. It is, therefore, important since many researchers (Driver 1988, Shuell 1992, Laurillard 1993, Hennessy et al. 1995) consider that misconceptions must be addressed before instruction takes place. It is, therefore, important to consider what other misconceptions sixth form students hold about this important process. For this purpose, sixth form students were interviewed.

In this second study, students even the most able, did not hold firm foundations on a number of basic concepts addressed in Kinchin's questions. In addition, with regard to the physico-chemico-biological principles students' ideas were essentially confused and they often resorted to rote learning so that overall principles were not well understood. There was therefore a picture of students attempting to internalise a realistic understanding of photosynthesis, but who failed to do so because their initial learning was so insecure.

From this preliminary work and misconceptions research students have real problems with an understanding of photosynthesis. What possible ways are there to improve students' conceptual grasp of this subject, specifically when computer mediated tools are used?

3.6 The research focus

From the discussion in Chapter 2 on computer mediated tools and the psychology of learning there is support for a number of approaches that should enhance conceptual understanding. Even so the empirical evidence that the computer per se or specific ICT tools bring about improvement is certainly not without its detractors. Part of the reason for this is the methodology employed in the measurement of conceptual gain, which is often by the use of the multiple-choice test. Another reason is that the various ICT programs lack a specific epistemology or have weaknesses related to specific aspects of the learning process, such as adequate feedback and scaffolding. Another, though not unrelated factor, as to whether ICT tools are effective or not, is the level of assistance given to the learner by an expert during the

running of a program. Such assistance may not only make the learning process more meaningful to the learner, but may inform the researcher / teacher about the concept in formation rather than the end product. Other ways in which this conceptual development may be explored is by the discourse that occurs between the users, if they work in pairs. Thus the computer may be used as a tool in the students' construction of knowledge.

Most recent psychological theories promote a constructivist approach to learning and two most important advocates, Piaget and Vygotsky, take rather different positions on cognitive development, concept development, the role of language and problem solving in the construction of knowledge. For Piaget, cognitive development takes the primary role, whereas for Vygotsky it is concept development and language that are most important. For Vygotsky, concept development in the sciences pushes cognitive development ahead and language reflects those concepts in the making and in their final form. For Vygotsky also the role of an expert other in the learning process working within the learner's zone of proximal development was essential in the mediation of learning. Therefore, any research involving learning with computers should supply a rich source of data from which to assess learners' understanding.

When designing software to support learning, account must be taken of a number of factors, such as the type of ICT tool to be used, the psychological theories of learning already referred to, but also to the pedagogical practices that will enable computers to be used most effectively in the classroom. Thus

Laurillard's discourse model provides a tightly scaffolded schema whereby the learning process can proceed.

Finally, the research needs to focus on a conceptually difficult topic, which is photosynthesis. It is inherently difficult, because many of the ideas are abstract in nature, because students lack positive attitudes to learning about plants and because they may carry with them many misconceptions from past instruction. It is, therefore, an ideal domain with which to evaluate the strengths and weaknesses of program designs in terms of their effectiveness in promoting student learning.

Therefore when analysing students' use of software in order to refine software design, it is necessary to consider the following:

- software itself, that is the type of generic tool used, and the particular value ascribed to it;
- types of generic tool used should be clearly distinguishable as, say, amongst multimedia, simulations and adaptive media;
- expected strengths/weaknesses of the software should be identified in terms of whether or not it encourages conceptual understanding, problem solving or both;
- degree of feedback in the systems should be determined – is it just by mct or more analytical and/or adaptive?
- how well the system determines a specific outcome, in other words how prescriptive is the software;
- to what extent the system is capable of being used by students independently / in groups;

- open-endedness of the software and the advantages that the degree of advantage that such open-endedness confers on students' conceptual understanding;
- advantages from the teacher's point of view of a highly scaffolded system;
- conceptual gains from group work or activity using different generic tools;
- relationship between conceptual gain and prescriptive (cognitive software) compared to open-ended (constructivist software);
- methodology of data collection which, as well as codifying conceptual gain and analysing it statistically, should provide for:

1. Accounts of group work that recognise the powerful influence of the teacher or tutor on learners' computer based collaborative work; (Mercer and Fisher (1992 and 1997)) observed that it is the teacher's responsibility to ensure that children's computer-based experiences contribute to their education. This cannot be relegated to even more sophisticated software or to the children themselves.

2. Rich descriptions, conceptualisation and evaluations of the ways in which teachers and tutors attempt to support or scaffold learners' collaborative learning with computers.

3.7 Research questions

The research questions that this thesis addresses can therefore be summarised into four groups

1. What are the generic features of photosynthetic software that can support student learning?
2. What are the pedagogical strengths and weaknesses in relation to a pedagogic discourse model, such as that advanced by Laurillard?
3. How can this model inform the construction of a support system to encourage an active teaching strategy in the classroom?
4. How can these findings assist with recommendations for classroom teachers when evaluating and using different pieces of software that can be incorporated into a holistic teaching strategy?

3.8 Stages of research

3.8.1 Classification of software in the domain of photosynthesis

With regard to Question 1, the software programs that are available in photosynthesis can best be considered to have characteristics that enable them to be distinguished in three, though not totally exclusive, ways, which are by their:

- generic type;
- level of feedback;
- interactivity.

Generic type, in this instance essentially following Laurillard's categorisation of computer software, is used to separate programs into three distinct groups: those that are hypermedia, others that are interactive and finally those that are adaptive. Since the definition of hypermedia is somewhat confused, the term multimedia program is used in this research. These are programs that may or may not offer a route through which learning may proceed but will contain some or all of the following: pictures, text, sound, animation, music

and full motion picture. Interactive ones are considered here as those that primarily investigate the effect of variables on photosynthesis and include simulations, microworlds and models. Adaptive programs embody a teaching strategy, which changes depending on the user's actions.

3.8.2 Pedagogical strengths and weaknesses of software

In respect of the second question, whatever the generic descriptor may be, programs do not always possess the exclusivity that the above descriptions might imply. These descriptions tell us more about the teaching platform, together with some of the pedagogy, than whether the student becomes engaged in a pedagogical dialogue with the teacher. So in order to investigate first of all the effectiveness of Laurillard's Discourse Model, it is most appropriate to determine not only the level of feedback within each program but also the pedagogical value that student interaction with it actually is. However, whilst simulations, microworlds and models expect student interaction, it is not necessarily clear that such interaction is meaningful, since students by their actions are unlikely to make explicit their lack of understanding. It is, therefore, important in the first instance, to classify programs on the quality of the feedback provided. For example, is the feedback available as the learning proceeds or is it in the form of end of topic tests? Finally, does the feedback provide assistance to students in order to aid their understanding, which means is there a degree of interaction?

3.8.3 Support systems for computer software in the classroom

The third research question is the major one involving data collection. First of all predictions about the educational value of a number of photosynthetic programs are necessary. This is based on a number of factors, but principally

on the pedagogy and the level feedback, which is based on Laurillard's Discourse Model, and on the content. The level of feedback is coded on a 1-5 scale, with level 5 having feedback that might well address most student questions.

Nevertheless, it must be emphasised that the degree of interactivity with the user is of profound pedagogical importance, too. Programs that encourage both collaboration and discourse as well as generate the greatest cognitive conflict perhaps, especially in students whose conceptual understanding of photosynthesis is weak may be those that are most successful. Perhaps, as a result of such interactive behaviour students will be encouraged to become metacognitive.

In addition, the researcher conducts cognitive walkthroughs of the programs in order not only to establish how easy or difficult it may be for the students to use them in a practical way in the classroom, but also to determine where further assistance may be necessary, in order to carry out specific tasks.

These procedures, identification of the type of software, the level of feedback and interaction, and the cognitive walkthroughs together inform the research of the most appropriate programs to use in the data collection phase of the Pilot, and Main, Study.

In the first instance, in the data collection phase of the Pilot, the role of feedback in the selected programs and how it supports the learner is investigated. In order to reduce variability of those students taking part in the research programme, or at least to recognise this variability in conceptual

understanding at the outset, a pre-test will be administered to the research group. This is based on the work of other researchers, at the pre-A level, but also on the interviews carried out with sixth-form students during fieldwork. Students are brought to the pilot, for their cognitive walkthrough who have a sound understanding, with few misconceptions about the basic principles of photosynthesis, since those who do hold a body of misconceived ideas have not only difficulty in overcoming them, but also in developing new levels of understanding. This study is not intended to further misconceptions research, but it is acknowledged that serious misconceptions do exist, even amongst those who teach the topic.

The photosynthetic topic that is studied is the one that students and teachers acknowledge as being difficult, which is the light-dependent phase. The pre-A level test contains general questions about this topic, too.

Recent researches have demonstrated the value of collaboration and discourse in enhancing student understanding when using computers. This research acknowledges these findings and therefore students work in pairs, generated on the basis of personal friendships.

The time span for any continuous use at the keyboard depends on the extent of student talk and explanation. The time is the overall period that students take to complete the task, which is to study the materials on the light-dependent reaction. All work is audio and video recorded in order to provide evidence of the discursive interactions and other behaviours, such as periods of silence, that take place. At the end, a post-test is administered.

The third research question is answered further in the main study and the fourth one is addressed as a result of the findings from this research. The suggestions from the Pilot that students experience certain learning problems when using software that has very little feedback is used to form the basis on which to make predictions about two pieces of contrasting software (*Explorer™* Photosynthesis and *S103 Discovering Science*). The first piece (*Explorer™* Photosynthesis) contains very little intrinsic feedback, but lots of interactivity and the second (*S103 Discovering Science*) holds a variety of feedback opportunities. As far as possible, other characteristics of the software, such as the factual information provided, remain the same.

Once again, as in the pilot, a pre-test will be administered and the researcher will then conduct cognitive walkthroughs with the students testing the software. This is undertaken in order to further clarify the difficulties that students are likely to encounter and where they need further assistance. Students use the software and the points at which assistance is required is noted and acted upon by the researcher only when discussion between pairs fails to realise a solution, so that progression through a program to completion is possible. All the work is recorded on audio and video taped as well as by hypercam in order to provide evidence of the discursive interactions and other behaviours, as well as to reveal on screen responses to the activities required by each program.

Post-tests are again given immediately after program operation and this time after a time delay. It is hoped that this research suggests the type of program most suitable to address misconceptions and assist understanding of the

light- dependent reaction of photosynthesis. Also, on the basis of student discourse and students' requests for help during the running of the programs there is the possibility of integrating interventions and or adding remedial materials that enhance understanding still further. It is also hoped that generalities about learning with programs of similar designs are possible, not only in other topic areas of the same subject, but also in other domains.

3.8.4 Recommendation for classroom teachers

With regard to final question, the foregoing research has been set up not only to demonstrate the effectiveness or otherwise of software on the light reaction of photosynthesis per se, but also to provide guidance to teachers when evaluating pieces of software for use in the classroom. If, for example, there is a demonstrable need for constructive dialogue between the students and even the teacher and students when certain types of software are used in the classroom, there are implications for the kinds of educational practice that are most successful and on the demands made by the students on teachers' expertise.

Finally, the value of this research is determined by how well it informs teachers as to how best to use different software programs in the classroom.

This 'use' might include:

- additional props that are required to make each of them more effective;
- the extent to which discourse aids learning with any one of them.

Chapter 4 The Pilot Study

4.1 Introduction

As is described in Chapters 2 much has been written in order to disseminate knowledge and understanding about computers in education. One essential aspect is a classification of the types of programs available. Various authors attempt to classify ICT tools (Rodriguez 1997), Goodman & Berger (1998) and Laurillard (1993), who also makes a formal link between the efficacy of the tool type in developing knowledge with understanding and a model of learning (Laurillard's Discourse Model). For this research three types are identified: hypermedia/multimedia, interactive media and adaptive media. According to Laurillard's model interactive programs should be more effective than hypermedia and adaptive media the most effective in the development of knowledge and understanding.

There is research evidence that suggests interactive programs do enhance student knowledge in science (for example, Geban et al. 1992, O'Shea et al. 1993, Williamson & Abraham 1995, Barnea & Dori 1999, Akpan & Andre 2000) and that hypermedia/multimedia programs generate positive attitudes to learning (Beichner 1994, Blackmore & Britt 1990), though their effects on knowledge and understanding are more equivocal (Blackmore & Britt 1990, Sewell et al. 1995, Liao 1999, Shapiro & Niederhauser 2004). The evidence for enhancement of learning in science when using adaptive media is limited, though one paper (Dewhurst et al. 2000), does suggest knowledge enrichment where this type of program is employed. Therefore most of the studies in this genre illustrate that students do learn whatever the conditions. There is, however, nothing to suggest from this limited evidence to support

Laurillard's contention that one type of program delivers knowledge and understanding more effectively than another, since all of the studies employed only one type. Neither is there incontrovertible support for the view that programs are more effective than traditional teaching or tutorials, since many of the studies measured gain against a control group, which was taught by traditional methods, where often there were no significant differences between the two groups. Perhaps it is less sensible to see whether students learn with computers or not, than to see which characteristics of computer programs can facilitate learning, so that teachers may be provided with a check list for the selection of suitable computer programs for their classes. The present research sets out to test the teaching strengths of two generically different pieces of software. Both are multimedia programs, one of which provides a pre-determined route to a specific goal and contains stage by stage feedback and scaffolding and, since it contains an explicit teaching strategy, may be defined as adaptive, the other is, on the basis of Laurillard's classification, interactive, and does not provide a pre-determined route, involves making predictions and doing simulations, but contains almost exclusively only intrinsic feedback.

The topic chosen for this study is photosynthesis. Whilst extensive research on students' conceptual understanding of photosynthesis has been undertaken (Wandersee 1983, Haslam & Treagust 1987, Cho 1988, Marmaroti & Galanopoulou 2006), very little involves those who are more mature (Boyes & Stanistreet 1991, Lenton & Turner 1999). Even with these older students, the focus is on misconceptions that are frequently held by those in their middle years at school. This research investigates the

knowledge and understanding of photosynthesis that might be expected of students in an English sixth form or at first year undergraduate level and how programmes can be made to develop an understanding of this topic using different pieces of software. This Chapter describes the Pilot stages of this research, from the selection of the software to the signposts for the Main Study.

4.2 The selection of teaching programs

A search of suitable pieces of software on photosynthesis revealed only eight programs. Some of these were exclusively on this topic and include Cyber Ed, COGITO Model-It, CHEESEMAN Photosynthesis and LOGAL's Explorer program. The rest contained materials on a variety of physiological topics, though held subject matter on photosynthesis at a level equivalent to sixth form, or first year undergraduate, level.

Altogether eight programs were collected which included those in Table 4.1.

Title of program	Source University/Publishing House / Country of origin
Plant Biology Tutor	Virginia Polytechnic Institute, U.S.A.
Photosynthesis, Cheeseman	University of Illinois, U.K.
Plant Physiology 2000	University of Sussex, U.K.
Biologica	Knowledge Books and Software, Australia
Photosynthesis Cyber Ed	Cyber Ed Inc., U.S.A.
Discovering Science, <i>Cells and Energy</i>	Open University, U.K.
Photosynthesis Model-It	Cogito Learning Media Inc., U.S.A.
<i>Explorer™</i> Photosynthesis 3.04*	Logal Software Inc. / Riverdeep Inc., U.S.A.

* hereafter called *Photosynthesis Explorer*

Table 4.1 Software programs on photosynthesis suitable for sixth form use

The aim of this analysis is to select two pieces of software that possessed different generic features and levels of feedback whilst still providing as much of the necessary factual material that a student would need to follow/study the Advanced Level Biology specification.

Each one was analysed for its ease of use, content, generic features, degree of interactivity and feedback. All are multimedia applications since they contain one or more of the following attributes: sound, graphics, animation and motion video in addition to textual material. The results for this analysis in terms of generic features, interaction, general feedback and test facilities are summarised in Table 4.2, whilst the quantity of content is illustrated in Table 4.3 and the degree of feedback in Table 4.4.

The contrasting pedagogies are those of learning through problem solving and discovery – hypothesis generation, hypothesis testing, conclusion and regulation - and learning based on Laurillard's Discourse Model, in which hypothesis generation and testing are just parts. In this model, for effective learning, there must be discourse between the learner and the teacher or computer program that includes five main aspects: apprehending structure and integrating parts (getting to know the structures and forms of representation), acting on descriptions (problem solving, testing hypotheses, feedback)), using feedback (relating actions to a goal in order to produce descriptions of events) and reflecting on goal-action-feedback.

The two pieces of software that best illustrated the differences between these two pedagogies are *Photosynthesis Explorer* – a simulations program and *Cells and Energy* – a tutorial. They held different approaches to the delivery of the photosynthetic topic and carried content that was more than adequate for A-level students. Nevertheless the differences between them are not so great thereby enabling a restricted number of the salient features that facilitate learning to be explored.

Features of software	Name of software							
	Plant Biology Tutor	Photosynthesis Cheeseman	Plant Physiology 2000	Biologica	Photosynthesis Cyber Ed	Discovering Science, Cells and Energy	Photosynthesis Model-It	Photosynthesis Explorer 3.04
Multimedia	✓		✓	✓	✓	✓	✓	✓
Multimedia and interactive	✓		✓	✓	✓	✓	✓	✓
Multimedia (with pre-determined route)					✓	✓		
Multimedia (with hypertext and capable of routing)				✓				
Multimedia (with hypertext and without routing facility)			✓				✓	✓
Level of interactivity more than clicking forward and backward buttons			✓	✓	✓	✓	✓	✓
Feedback in support of factual answers			(✓)	✓	✓	✓		
Feedback primarily/entirely from results of simulations	✓						✓	✓
Problem solving in a simulations format or as a microworld							✓	✓
Drill and practice (tests)				✓	✓			
Adaptive elements (tutorials)				(✓)	✓			
Adaptive elements (integrated within teaching and learning)						✓		

Table 4.2 Generic features of software

Key: shading represents programs selected for the study

Level of photosynthetic content presented by software	Name of software						
	Photosynthesis Explorer 3.04	Photosynthesis Model-It	Discovering Science, Cells and Energy	Photosynthesis Cyber Ed	Biologica	Plant Physiology 2000	Photosynthesis Cheeseman
Level 1 Below A-level standard							
Level 2 Limited to effects of variables on rate							✓
Level 3 Factual material presented at a sub-cellular level only							
Level 4 All events covered, but factual content limited					✓		
Level 5 All events fully covered				✓		✓	✓

Table 4.3 Content of software

Level of feedback	Name of software						
	Photosynthesis Explorer 3.04	Photosynthesis Model-It	Discovering Science, Cells and Energy	Photosynthesis Cyber Ed	Biologica	Plant Physiology 2000	Photosynthesis Cheeseman
Level 1 Feedback entirely from experimental simulations							
Level 2 Feedback mainly from experimental simulations	✓						
Level 3 Feedback occurs in a separate test/tutorial section, as right or wrong response							
Level 4 Feedback occurs in a separate test/tutorial section, as right or wrong response, with comment					✓	✓	
Level 5 Feedback occurs to questions as an integral part of the teaching strategy							✓

Table 4.4 Level of feedback in software

Discovering Science (*Cells and Energy*) contains a distinct pedagogical framework that closely matches Laurillard's Discourse Model. Of the five aspects of the learning process included in this model, this program carries elements of all of them: (1) there is a clearly defined structural framework and a procedure whereby structures may be integrated in order that students may comprehend whole processes (including summaries of events) (2), there are descriptions (in the form of questions) to which students respond and feedback opportunities (including feedback to question responses) (3), as well as the requirement to use feedback (in order to elicit a new response) (4) and to reflect on the answers already given (5). This program is particularly strong on three of these aspects, 1, 2 and 4.

Photosynthesis Explorer, whilst also being in a multimedia format, is a complex program. It allows both for free discovery of aspects of the photosynthetic process and for a more guided discovery approach. Whichever approach is used, hypothesis testing and problem solving using simulations form the principle means of learning. When used for more or less free discovery, the elements in the menus of Explorations and Core Enquiries may be accessed in any order using hypertext, though there is then a prescribed route within each element. So far as Laurillard's Discourse Model is concerned, the program is inherently problematic on three of the five aspects, notably apprehending structure, integrating parts and using feedback (for concept development). Its strength lies in acting on descriptions, particularly hypothesis testing, problem solving using simulation exercises and producing descriptions (3) as well as on reflection from the results of these simulations

(5). These differences may be reduced with a more guided approach in which possible student problems relating to apprehending structure and integrating parts may be enabled by a more guided approach, making the program more akin to a tutorial simulation. Thus the major differences between the two programs relate to the high level of problem solving activity through the simulation of experimental results in one as opposed to the high level of feedback in the other.

4.3 Methodology for the study

4.3.1 Theoretical background

This research aims to gain insights into the ways in which participants learn with different pieces of software and to understand essential features of multimedia programs that facilitate learning. Piaget and Vygotsky suggest human learning is far more complex than can be discovered from the generalisations made as a result of tests in tightly controlled studies. From their perspective is the view that knowledge is personal, subjective and unique to an individual, so there is a rejection of the scientific method, at least that of pure objectivity.

In the social sciences, the research paradigms, at least at the extremes, reflect two views of knowledge. For those taking a positivistic view of human behaviour, together with the methods of natural science applied to a piece of research, Cohen & Manion (1989) have ascribed the term 'normative paradigm'. For those with the opposing view and concern for the individual they have coined the term 'interpretive paradigm'.

Whilst there are these two extreme views of knowledge, its acquisition and its research methodology, Merton & Kendall (1946, pp. 556-557) state that *'social scientists have come to abandon the spurious choice between qualitative and quantitative data: they are concerned rather with that combination of both which makes use of the most valuable features of each'*.

4.3.2 Quasi-experimental approach and triangulation

This theoretical background helps to explain the methodological approach adopted by this research. It uses a quasi-experimental methodology in which different types of data are collected, which is called triangulation. The quasi-experimental nature of the research stems from the design of the procedures used, the methods of analysis, but above all on the need to gain insights not only on what it is that students learn about photosynthesis using the CD-Roms, but also the circumstances and actions that encourage it. It is not possible to control all the variables and most importantly the participants taking part cannot be randomised between the two programs either. It is proposed to assign pairs of students to the two pieces of software selected and to investigate the effects of the software on students' behaviour, both during the time that they work on the software and by their performance on tasks after their work on the programs had been completed.

In the past, research methodologies have, in some cases, concentrated on objective tests, such as that of the pre-and post-multiple choice type (mct), which may in part account for the failure to deliver student change, as suggested by Evans (1994) when investigating hypermedia programs. Since a rich source of data is required, several methods of data collection are

adopted. Cohen & Manion (1989) describe this technique of triangulation as particularly valuable in education. In this research it is not only important to discover the effects on the behaviour of participants after using the programs, but also the possible causes of these differences in relation to the perceived strengths of the two pieces of software and in respect of student discourse. The specific types of triangulation adopted are those of theoretical and methodological triangulation. Theoretical because the research is looking at different teaching strategies and learning models and methodological because it seeks to validate its findings from a variety of data sources, both quantitative and qualitative. Changes in outcomes are to be judged by differences between pre- and immediate post-test scores and delayed post-test responses and their causes by the nature of participant discourse as well as by responses to questions in the programs themselves. Whilst pre-test and post-test data are to provide for some degree of generalisation with regard to the research, the discourse analysis is to be interpretive and more restricted to this study alone. The discourse can also provide insights into the roles of guided discovery, cognitive conflict and its resolution, scaffolding and feedback in terms of the development of a sound understanding of photosynthesis. In addition, whilst the test scores are to be purely quantitative, the tests themselves must allow participants to give more than a purely objective response, thereby providing more evidence as to the clarity and understanding of that objective response. Once again, this might provide further evidence for the value of the programs and discourse in developing in the participants a partial understanding of photosynthesis and therefore of their zones of proximal development (Vygotsky 1962 and 1978).

If talk and/or purposeful interaction are important, which they undoubtedly are, what research tools are available for studying them? Various researchers have handled data from this in different ways, first for example, Barbieri & Light (1992), Teasley (1995) and Underwood & Underwood (1999) have dealt with talk by effectively reducing it to defined categories, which in turn lend themselves to statistical analyses and second, an interpretive approach (Barnes 1976, Maybin 1994, Mercer 1995) in which analysis is by transcribed extracts. The strength of the first methodology is its ability to analyse large amounts of data. Its persistence is partly due to a well-established methodological tradition, systematic observation (Croll 1986) and to the wish of funding bodies to discover whether more students could be taught as or more effectively using the computer as opposed to more traditional methods (Yilditz & Atkins 1993). Edwards & Mercer (1987), Draper & Anderson (1991), Crook (1994) and Mercer & Wegerif (1999) point to its weaknesses. Edwards & Mercer (1987) outline its failure to report on the original data, Mercer & Wegerif (1999) to show causal relationships, Draper & Anderson (1991) to acknowledge ambiguity in coding and Crook (1994) to demonstrate the developmental and evolutionary aspects of discourse. The strength of the second is that it enables both the evolutionary aspects of the discourse to be observed and to make available all the material for inspection and future research.

Categorical coding schemes are, therefore, probably inappropriate tools to use for studying the process by which learners build shared understandings, and the use of experimental studies involving brief circumscribed sessions of

computer based collaborative work is far from ideal. Crook (1999) and Scanlon et al. (1999) emphasise the necessity of and difficulty in the study of temporal dimensions of collaborative activity. Indeed, the picture becomes more blurred when students are working in front of a computer screen, since there may well be periods, as students working in groups, when they may interact less, because of shared assumptions that do not need to be verbalised. Such situations are important, since they may indicate reflection or a metacognitive aspect of learning, which has led some authors, such as Azmitia (1997) to question whether our fascination with peer interaction has gone too far.

Therefore, in the present study, the analysis needs to categorise activities not only in general terms, such as feedback, scaffolding, periods of silence or quiet reflection and time them, but also as participant discourse events in terms of Laurillard's discourse model to assess the evolutionary nature of the discourse from say apprehending structure to reflection on-goal-action-feedback events. In addition, the form in which the discourse itself is to be presented needs to be addressed.

The evaluation of software overall is, therefore, best looked at by a multifactorial / triangulation approach, which involves objective tests as well as a more observational, student-centred stance.

4.3.3 Validity and reliability

As with experiments, the importance of validity and reliability cannot be underestimated as potential threats to quasi-experimental researches. The concepts of validity and reliability are important to bear in mind in experimental design and can be explored briefly in terms of the post-tests. In this research, post-test questions are used to make generalisations about the strengths and weaknesses of two multimedia programs in delivering to students an understanding about photosynthesis. However, whilst they might be reliable tests when used with different groups of respondents, this may not be the measure that was intended. It is, therefore, important to reduce the risk of invalidity as far as possible, which will be described in this Pilot and in the Main Study.

It is useful to explore this concept of validity a little further in the context of the present study by outlining some of the different validation procedures that need to be considered. Cohen & Manion (1989) divide it into internal and external validity and these are discussed in the context of the present study below.

Considering internal and external validity in this current research three broad areas need to be considered in terms of internal validity. Firstly, participant validity needs to be established by determining their age, background and topics of study prior to data collection. Secondly data validity must be enhanced by ensuring that the tests are free from bias and cannot be answered by cues given in the way that they are set rather than in their actual content. Other data collected during the running of the programs, such as

audio material, must be audible, and visual material must be in focus. Thirdly, design validity must be established in that precisely the same instructions and situations are provided for all the participants.

External validity is more problematic in a quasi-experimental design, since all variables cannot be isolated and controlled (the participants, for example cannot be tested at the same time or put into fully randomised groups). Nevertheless Lincoln & Guba (1985) and Eisenhart & Howe (1992) have suggested that transferability is possible from studies without full control of variables, such as those with quasi-experimental design, by clearly stating the internal validation procedures. It is then, as Schofield (1993) suggests, possible for others to judge just how the results for an investigation may be generalised.

No matter how one looks at this sort of research there are threats to its validity that cannot be removed. However, what is needed is consideration of and an attempt to limit these threats in the Main Study by conducting a Pilot.

4.4 Aims

The aims of the Pilot were to:

1. Assess the suitability of the software for the Main Study in terms of usability, navigability and interface issues
2. Determine which specific aspects of photosynthesis could be realistically studied in a proscribed period of no more than 80 minutes
3. Trial the format, suitability, sensitivity and length of the test exercises

4. Investigate, when using CD-Roms, which other forms of data capture, including audio and video, were useful in providing clues as to the processes involved in learning about photosynthesis
5. Consider methods that might be used to analyse the data, including statistical analysis for the quantitative data as well as other analytical approaches for the qualitative material.

In order to plan the Pilot Study, it was important to consider the types of data required to provide information on each of the five aims. A summary of the information sought on four of these as well as the evidence source is set out in Table 4.5. Consideration of the fifth aim is to be found in the Analysis section of this Chapter.

Cognitive walkthroughs of the CD-Roms at this stage determines if participants are able to use the software to follow a pathway or pathways that enables them to develop an understanding of photosynthesis. They also provide evidence of the activities of each participant and the researcher during the running of the program, be they periods of silence, verbal interactions or psychomotor events of the participants, such as the clicking of the mouse or typing at the keyboard.

Aim of pilot	Information required	Evidence source
1. + 2. To evaluate participants' use of the CD-Roms	Problems related to navigation through the program	Audio and video tapes of participant activity and participant discourse with each other and with teacher
	Time taken to study the relevant section of photosynthesis	Any suitable timing device
	Difficulties with graphics, simulations and animations, including their accuracy and clarity	Observation by teacher and audio/video tapes of participant discourse
3. To determine the suitability of pre- and post-test exercises	Content of tests for A-level participants	Past A-level papers Interviews with participants Specifications of Awarding Bodies Content of CD-Roms
	Content of test at pre A-level	Wandersee and Kinchin using misconceptions research
	Format, number and type of tests	Previous research on multiple choice tests, two tier tests, concept goal, matching pairs and photosynthesis concept test
	Duration	Time of participant response
	Suitability	Evaluate participant response i.e. did they answer the question set
	4. To investigate which other forms of data capture are important in gathering evidence of learning with different types of software	Verbal interactions
	Operations with mouse	Video tape
	Operations at the keyboard	Audio/Video tape
	Periods of no audible activity	Audio/Video tape

Table 4.5 Aims, information required and evidence sources for the pilot

4.5 Materials, equipment and set up

4.5.1 Introduction to CD-Roms

Although the overall characteristics of the two programs have been outlined in Section 4.2 (The selection of the teaching programs), it is helpful in the present section to add to these features by providing a description of specific operations that participants in the Pilot, and eventually in the Main Study need to be aware of in order to navigate through them. This provides not only all the

major screen features, but also possible scenarios that may lead to the end of a task on photosynthesis. Consequently, the resulting discussion on any modifications to their use in the Main Study is addressed, in the first instance, in the context of the screen dumps provided here.

Only one of the pair, *Photosynthesis Explorer*, was extensively trialled in the pilot, because the other, from the Open University's Discovering Science Series (S103), contains a program (*Cells and Energy*) which is successfully employed by OU students in developing their understanding of energy storage and transference at the biochemical level together with ecological concepts. The merit of the OU's Discovering Science software is supported by data that are available from OU students' use of it when they work at home alone. There were therefore fewer concerns about the usability of this software when employed by sixth form students. Nevertheless one pair of participants did trial it in order to test how appropriate it might be for students at this level.

4.5.1.1 *Cells and Energy*

The CD-Rom Discovering Science (S103), Block 9 Continuity and Change contains six programs, which can be accessed on the first screen shown on the CD. The third program called *Cells and Energy* was employed. This program provides a Contents and Progress page, which contains six menu items, the last two of which are Introduction to Photosynthesis and Photosynthesis. Introduction to Photosynthesis delivers a two-minute audio/visual overview of photosynthesis, using a model cell and chloroplast. A screen dump of this stage is shown in Figure 4.1.

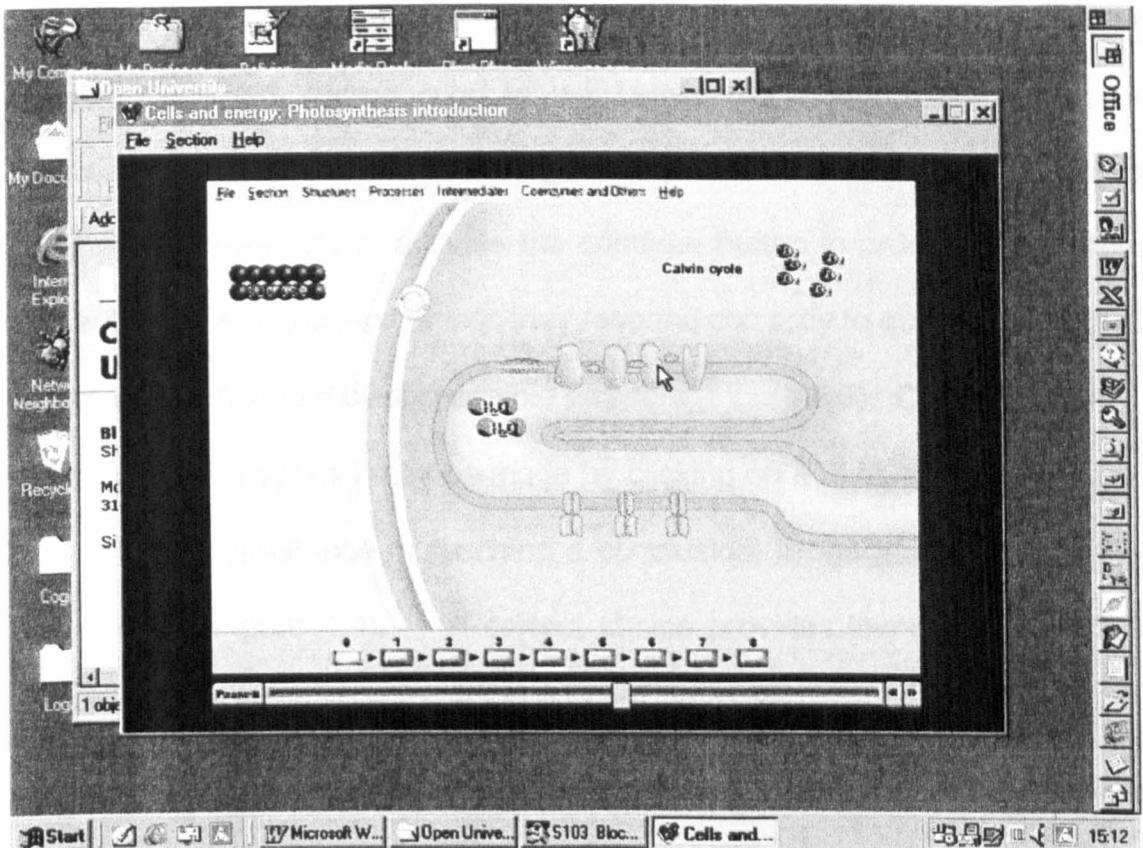


Figure 4.1 Discovering Science (*Cells and Energy*): introduction to photosynthesis

Users are then given a clear verbal instruction as to what they are meant to achieve by being given a task to perform, which is ‘Your task is to reconstruct the synthesis of a molecule of sucrose, starting with solar energy trapped in chlorophyll, water and carbon dioxide.’ At the end of this, the user is requested to go to the section called Photosynthesis where the task is presented.

In the section, Photosynthesis, a window appears that enables the user to commence at Step 1 by activating the Go button (Figure 4.2). There are eight steps which are subdivided and these subdivisions can be moved through by activating the continue button. Each step represents an important event, for example Step 1, concerns the splitting of water, Step 2 the production of $\text{NADPH} + \text{H}^+$ ultimately leading to Step 8, the production of sucrose. These

stages may be conveniently subdivided into Steps 1-3 (The Light-Dependent Stage), Steps 4-5 (Introduction to the Light-Independent Stage and Link Reactions) and Steps 6-8 (The Light-Independent Reaction and Sucrose Synthesis). Users cannot activate the continue button in order to move from one subdivision to the next unless they respond correctly to questions, each of which is accompanied by six possible answers (Figure 4.3). Clarification of each possible response may be made by clicking on it to reveal a description that provides assistance in reaching a conclusion, if one is not immediately forthcoming (Figure 4.4). A correct choice provides immediate feedback (Figure 4.5) as does an incorrect one in the same box.

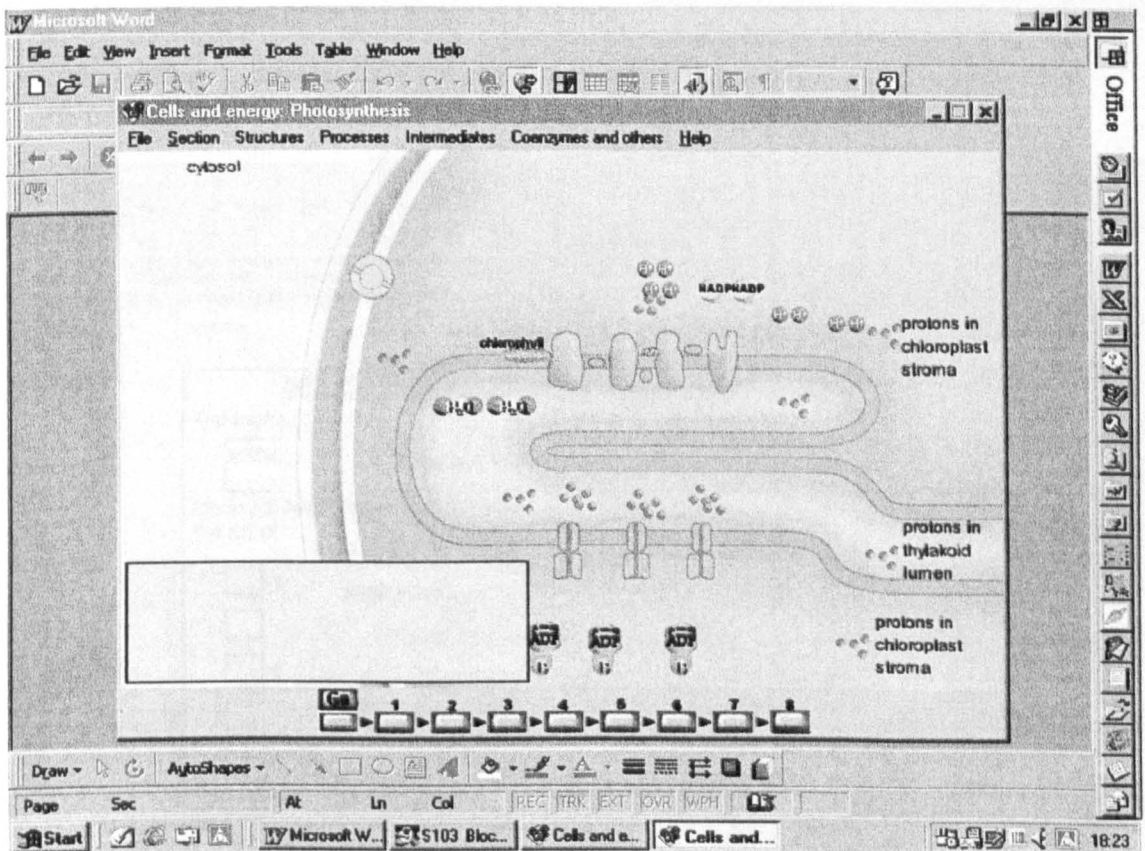


Figure 4.2 *Discovering Science (Cells and Energy)*: first screen showing go button

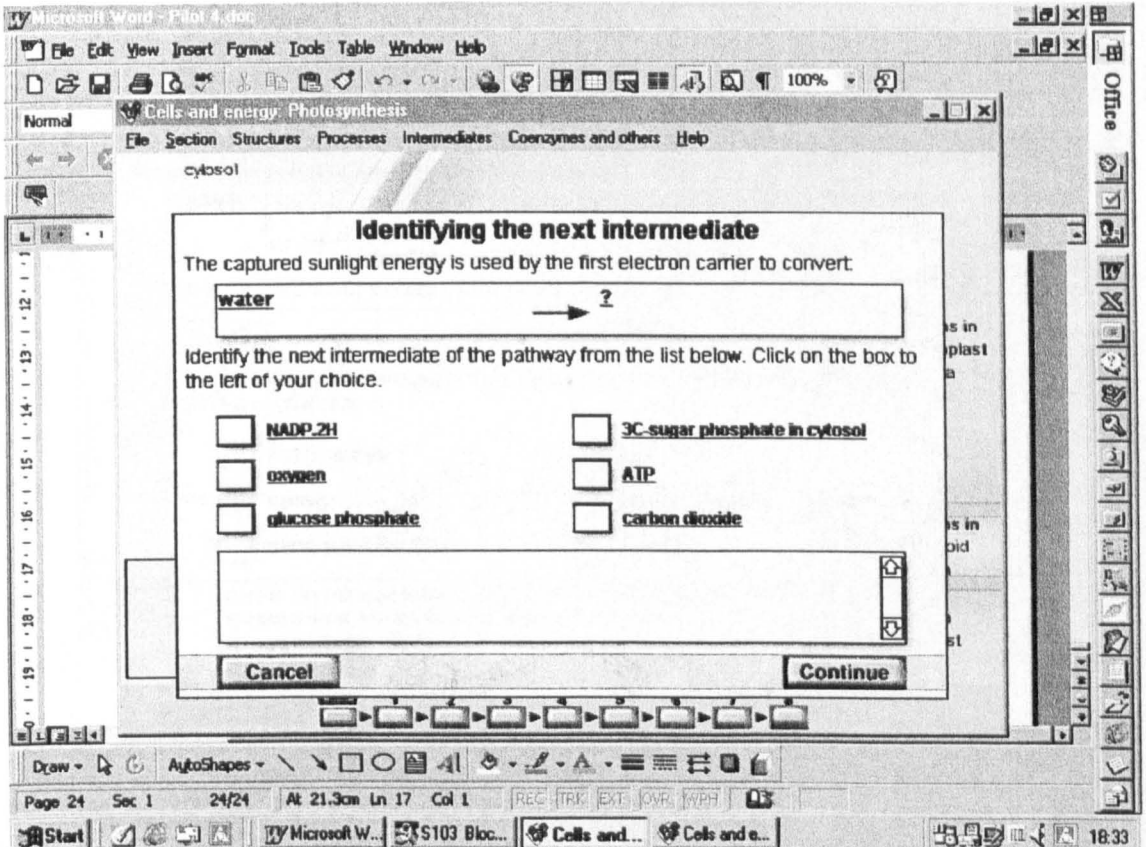


Figure 4.3 Discovering Science (*Cells and Energy*): first six options

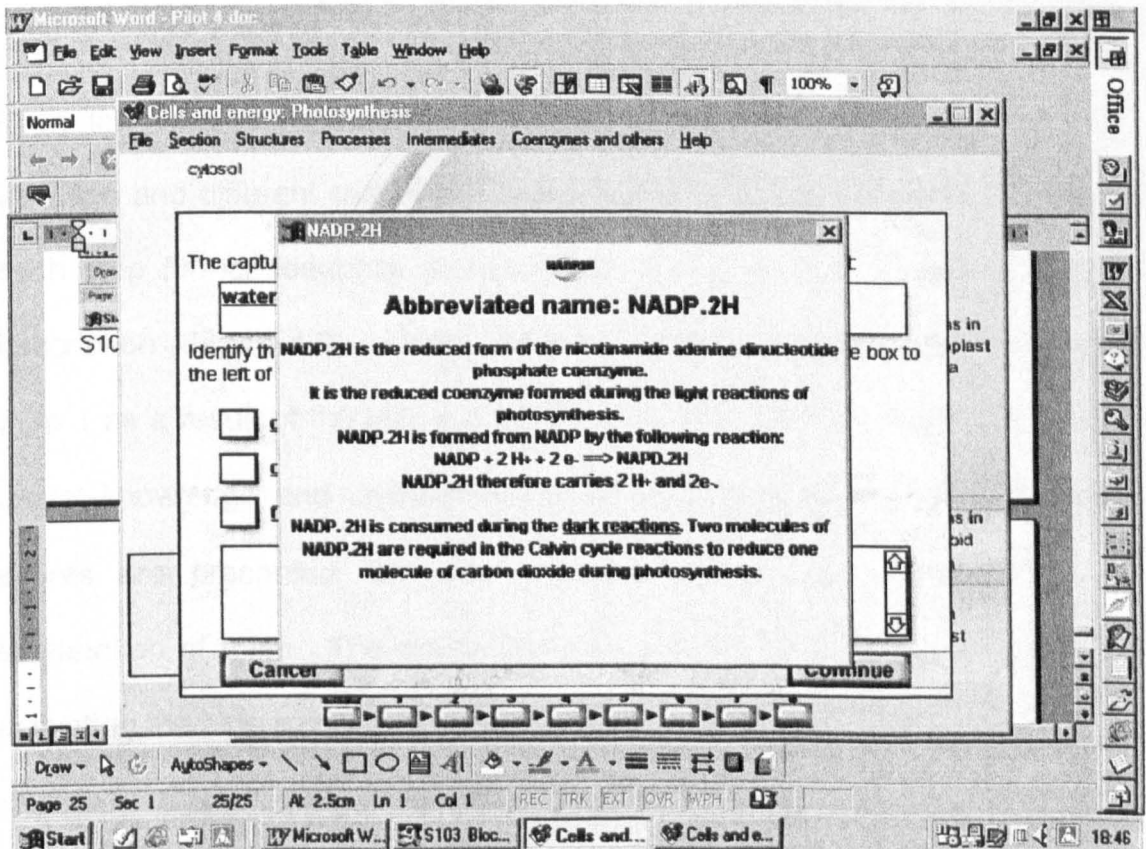


Figure 4.4. Discovering Science (*Cells and Energy*): additional feedback

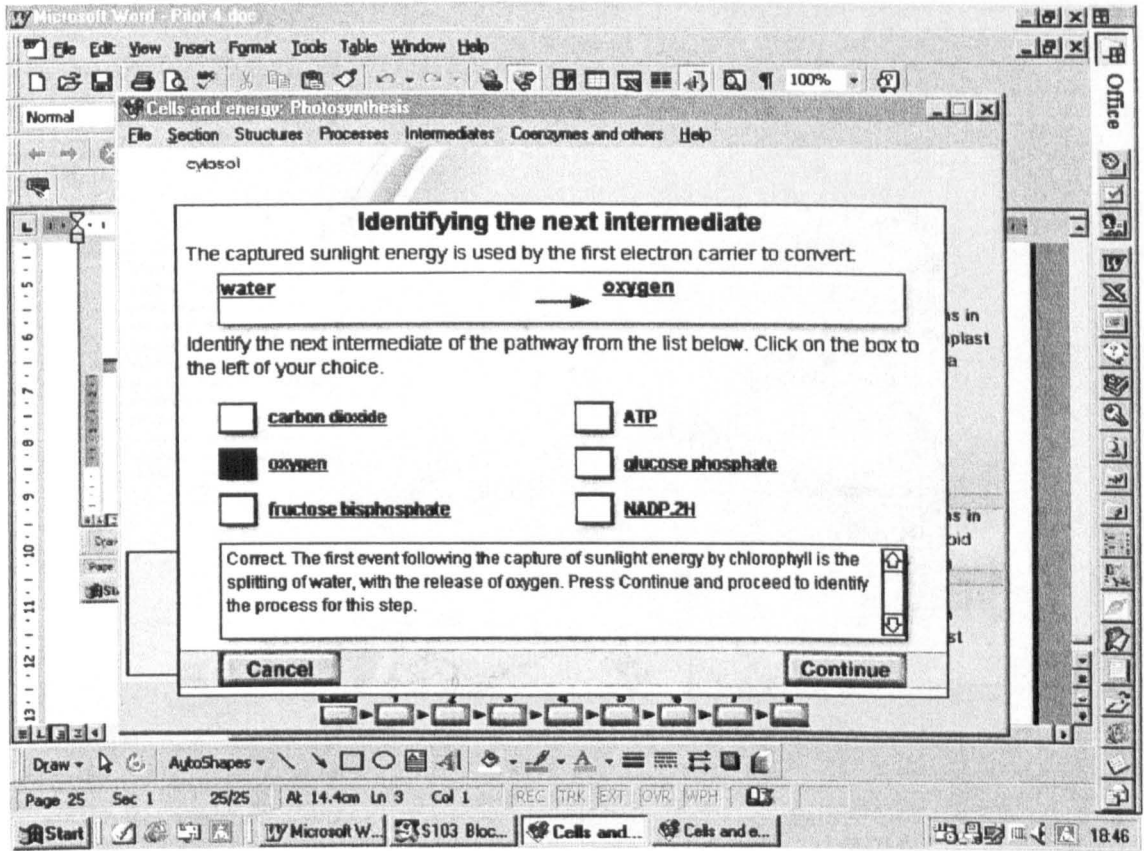


Figure 4.5 Discovering Science (*Cells and Energy*): correct choice with feedback

Each time the program runs the choice of answers changes to provide variation and different challenges every time the program is accessed. After each step further feedback is supplied in the form of an animation and a description (Figure 4.6). These provide a display of the events involved in Step 1 as a result of the users' previous correct responses. They add to the users' knowledge and understanding not only because the sites of these events are presented, but also because the summary also offers an explanation of them. The animations can be displayed again and again by activating the blue icon below the Go button.

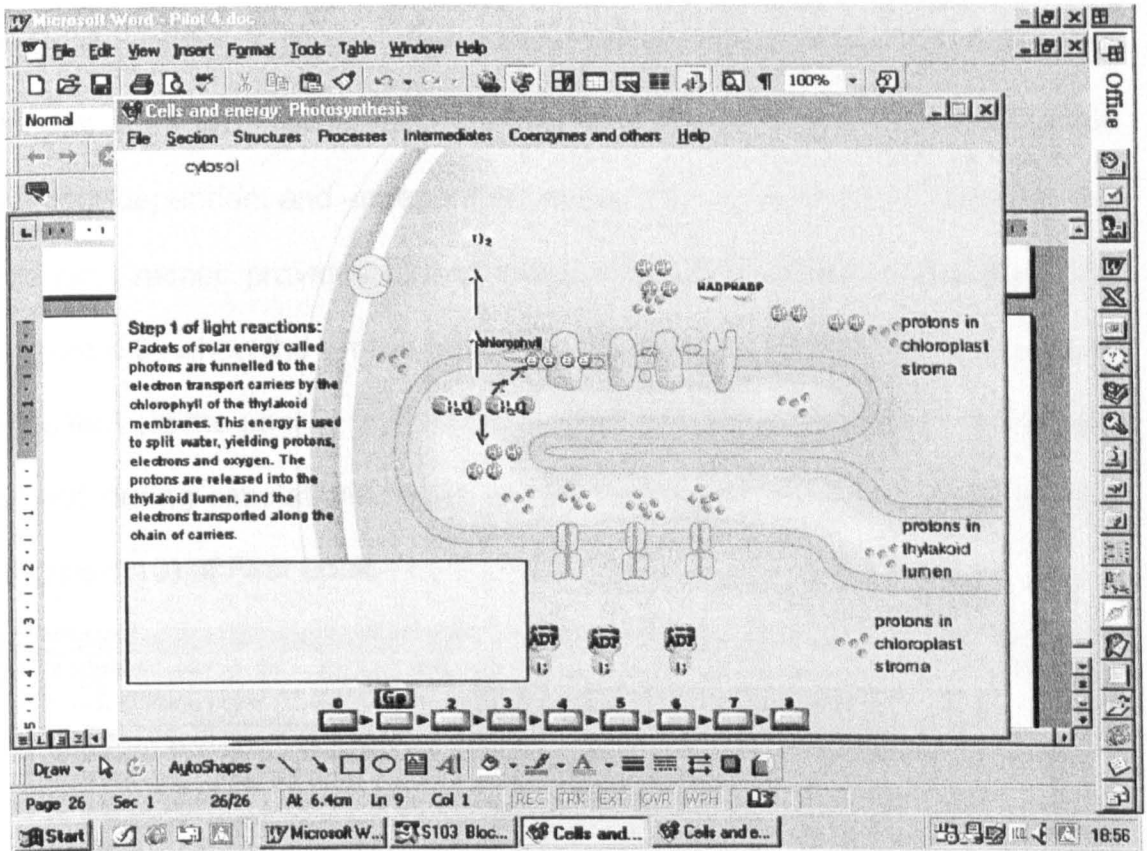


Figure 4.6 Discovering Science (*Cells and Energy*): summary at step 1

4.5.1.2 *Photosynthesis Explorer*

There are three sections in the Photosynthesis Main Menu, which is the teaching part of the program. The first is concerned with how to use the teaching program (First Look), the second provides background to photosynthesis (Explorations) and the third a sequence of discovery exercises using simulations together with some summary material (Core Enquiries).

First Look explains how users may use the various facilities on the program, including how to change parameters in simulations, stop them, step through them and block various reactions shown in a Mechanisms Window. An illustration of one of the windows is shown below with a model window either in leaf mode (Figure 4.7) or mechanisms mode (Figure 4.8). The one in leaf

mode shows the exchange of gases and the quantities of raw materials being used and products made. Mechanisms mode shows the reactions involved in the light-dependent and -independent stage of photosynthesis. Clicking on the chemical names provides further interactivity as is shown in the next slide (Figure 4.9) when the proton box is highlighted. In addition there are movie clips that aid the user in understanding how to change parameters at the start of and during simulations, as is shown on the bottom left of the final slide (Figure 4.10) of First Look.

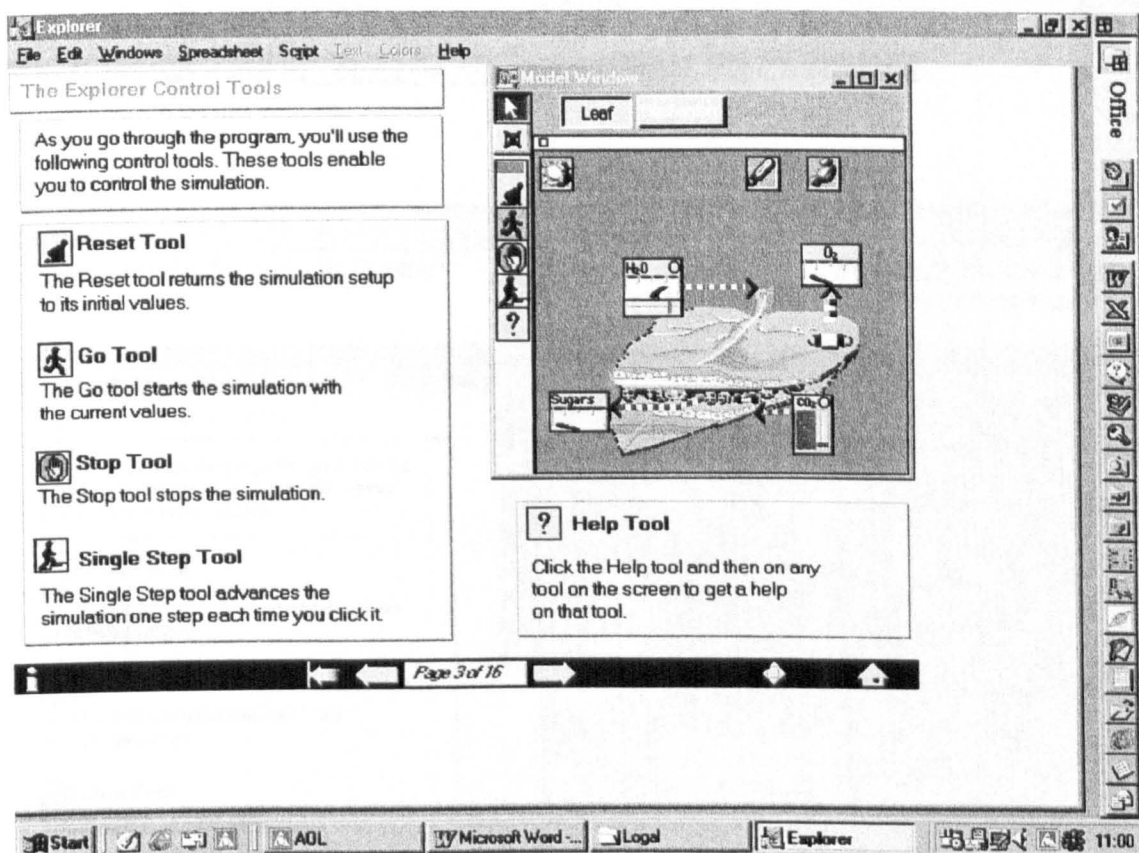


Figure 4.7 *Photosynthesis Explorer: First Look* – showing tools for simulations and the model window in leaf mode

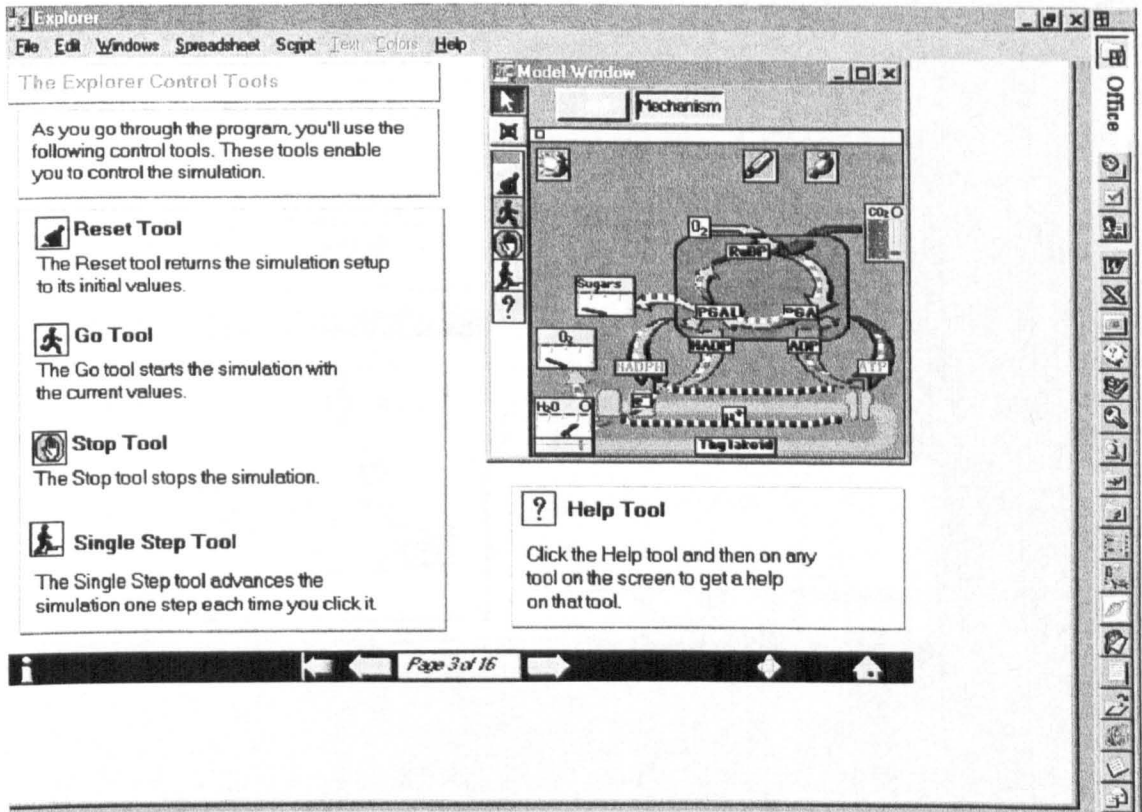


Figure 4.8 *Photosynthesis Explorer*: First Look – showing tools for simulations with the model window in mechanisms mode

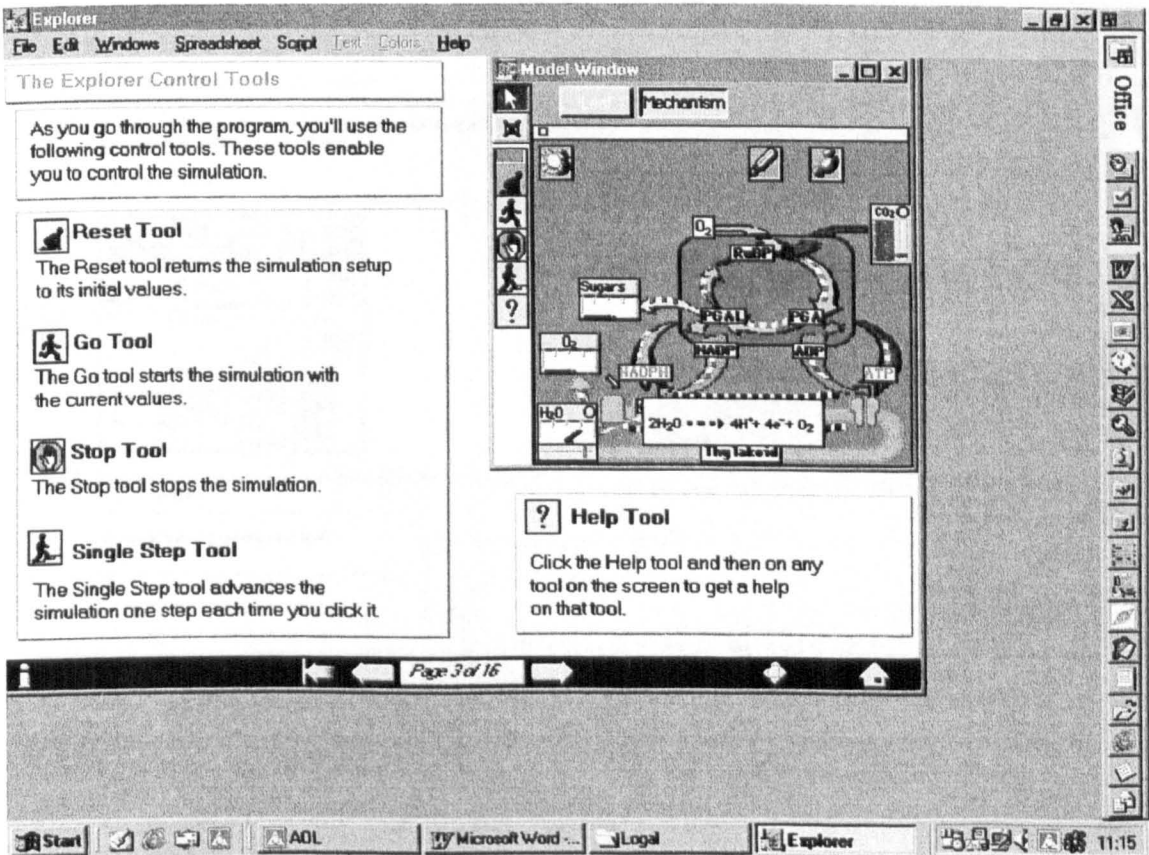


Figure 4.9 *Photosynthesis Explorer*: First Look – showing hypertext from proton box

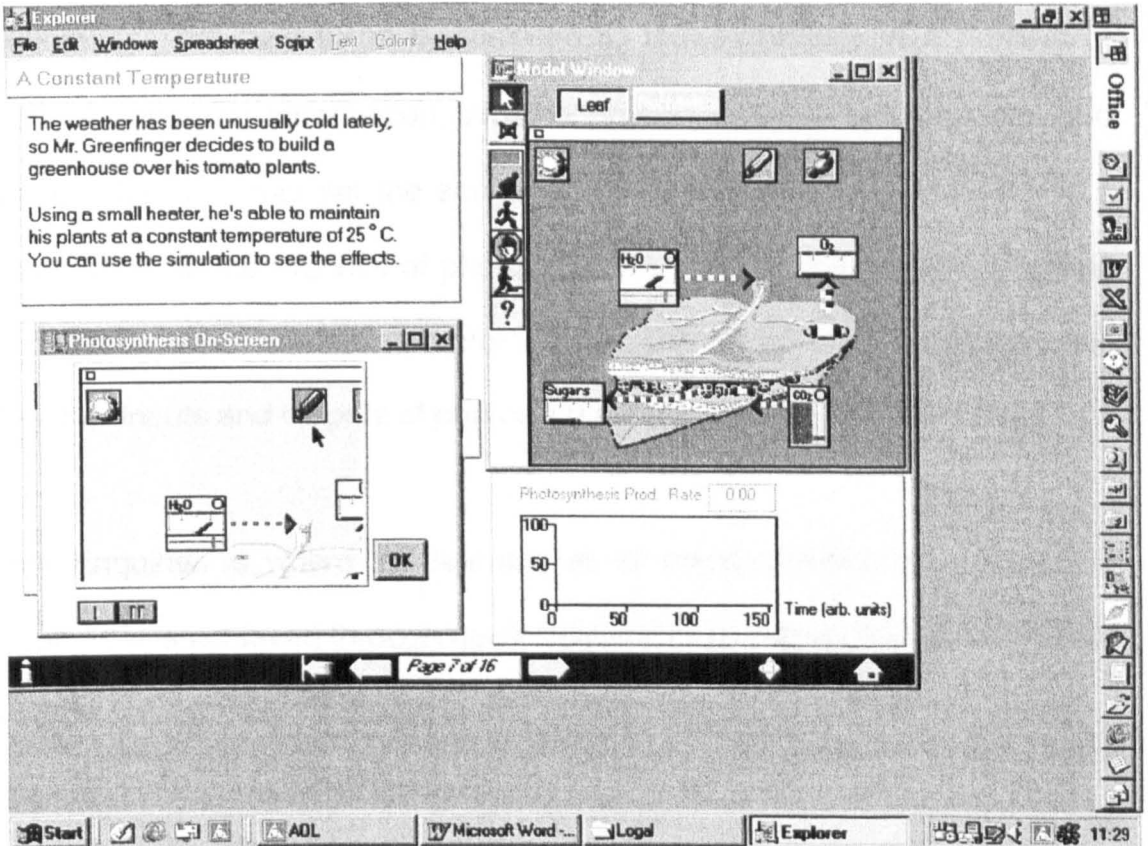


Figure 4.10 *Photosynthesis Explorer*: First Look – showing video clip 'Photosynthesis On Screen'

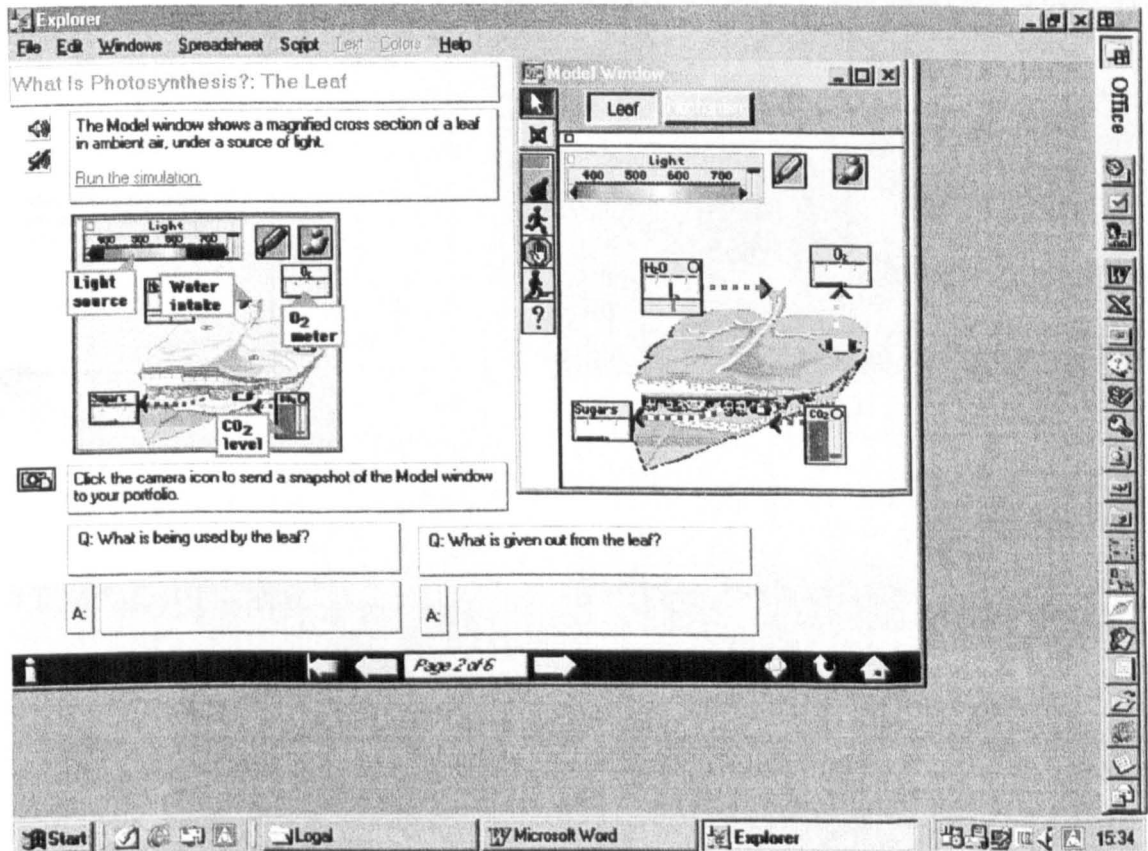


Figure 4.11 *Photosynthesis Explorer*: Explorations – showing simulations - chemical reactants and products

Explorations provides some background to photosynthesis in a number of sections, including Introduction, What is Photosynthesis, Light and Why are Leaves Green. They set the scene, so to speak, using simulations and a sound track on the process of photosynthesis. Figure 4.11 shows a screen dump on the section 'What is Photosynthesis?' in which users revise the basic chemical inputs and outputs of photosynthesis.

Core Enquiries is where the learning about photosynthesis is expected to occur. This is achieved through guided discovery by asking the users to make predictions, carry out simulations and to make conclusions. This practice is illustrated in Figures (4.12 to 4.14).

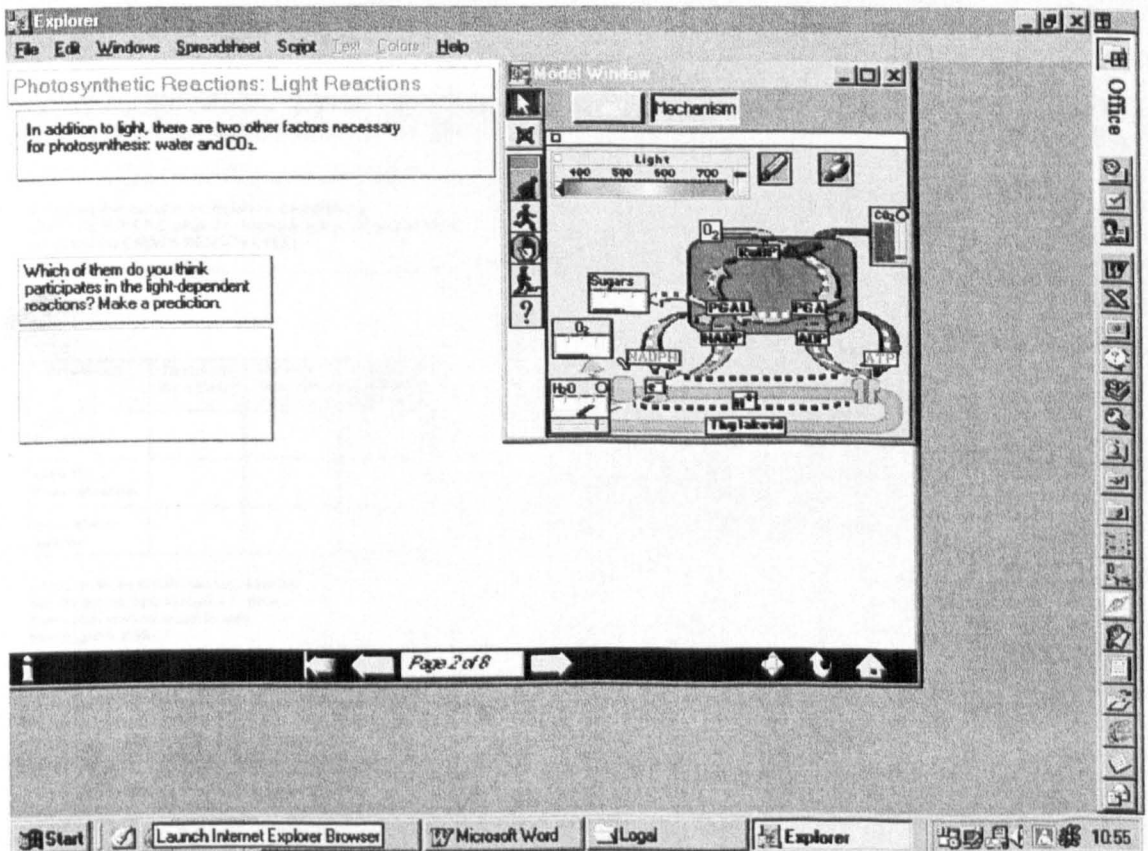


Figure 4.12 *Photosynthesis Explorer*: Light Reaction – making a prediction

Explorer

File Edit Windows Spreadsheet Script Text Colors Help

Photosynthetic Reactions: Light Reactions

To find out, perform the following steps:

- Run the simulation for approx. 50 steps until it stabilizes.
- Set $CO_2 = 0$ and observe what happens after another 50 steps, then stop the simulation.

Record your results in the table below by writing active/nonactive in the appropriate column(s).

Conditions	Thylakoid Reactions	Stroma Reactions	Oxygen Production Rate
Initial Conditions			
Zero CO_2 Concentration			
Zero Water Uptake			

Model Window

Mechanism

Oxygen Prod. Rate

0

150
100
50
0

Oxygen

Time (arb. units)

0 50 100 150

Page 3 of 8

Start AOL Microsoft Word Log Explorer 10:56

Figure 4.13 *Photosynthesis Explorer*: Light Reaction – carrying out a simulation

Explorer

File Edit Windows Spreadsheet Script Text Colors Help

Photosynthetic Reactions: Light Reactions

Reactions that occur in the thylakoid are called the LIGHT REACTIONS, while the reactions that occur in the stroma are called the CALVIN-BENSON CYCLE.

Conditions	Thylakoid Reactions	Stroma Reactions	Oxygen Production Rate
Initial Conditions			
Zero CO_2 Concentration			
Zero Water Uptake			

Based on these results and those for the isotope experiments in Inquiry 1, state from which environmental factors the oxygen is derived.

Model Window

Mechanism

Oxygen Prod. Rate

0

150
100
50
0

Oxygen

Time (arb. units)

0 50 100 150

Page 5 of 8

Start AOL Microsoft Word Log Explorer 10:59

Figure 4.14 *Photosynthesis Explorer*: Light Reaction – making a conclusion

Figure (4.12) shows that the users are asked a question about the inorganic chemical that is used in the light-dependent reaction of photosynthesis. They are then instructed (Figure 4.13) to carry out a simulation and to make observations about the stromal and thylakoid reactions and the oxygen production in a zero carbon dioxide environment. They are then expected to do the same in zero water (no illustration) and finally they are expected to conclude the likely source of oxygen (Figure 4.14).

Occasionally there are items of information, as in Figure 4.14, which here relates to the site of the light-dependent and -independent reaction, as well as summary comments at the end of each section. Since simulations are involved in many of the tasks, there should be plenty of verbal discourse and interactivity as Saljo (1996) suggests and this should also generate cognitive conflict as espoused by (Nickerson 1995 & White 1984) and of course reflection. This verbal discourse is likely to arise out of the observations made on the simulations and participants' current knowledge on the stromal and thylakoid reactions. The cognitive conflict may occur as a result of their observations here or from their conclusions earlier in this Light Reaction section, which relate to the source of oxygen. It is likely that as the users attempt to clarify conflicting ideas, they will need to refer back to previous conclusions or to run the simulations again.

There are ten sections altogether, which the screen dump (Figure 4.15) shows.

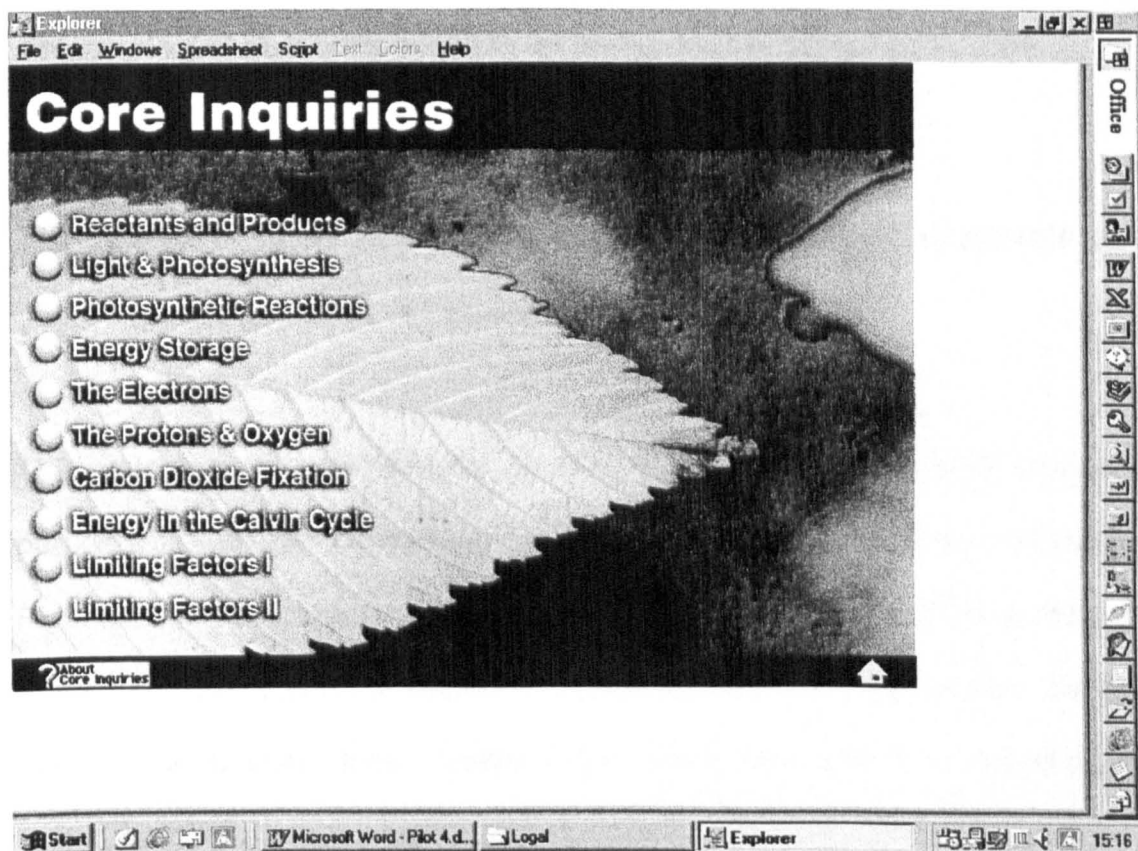


Figure 4.15 *Photosynthesis Explorer*: Core Enquiries – the menu

4.5.2 Introduction to test tasks

These were designed for two purposes. The first was to provide information about participants' understanding of basic concepts about energy and photosynthesis at the outset, as well as after using the programs. The second was to ascertain not only changes in conceptual understanding of photosynthesis required at A-level as a result of the use of the two programs, but also to compare the efficacy of each one in delivering this change.

As originally envisaged the bank of tasks consisted of (i) pre-advanced level and (ii) advanced-level materials. The pre-advanced level materials were

developed to gain insights into participants' understanding of basic concepts. The advanced-level tasks (questions) were set in the context of what participants might be expected to know after the use of the programs. The advanced-level questions set were for both pre- and post-program use.

4.5.2.1 Pre-advanced level tasks

Two groups of tasks were set these being match-paired statements and questions requiring short written answers.

The matching pairs set, based on the Kinchin (2000 (b)) format provided participants with two contrasting statements about a concept as is shown in Figure 4.16. Participants were expected to respond positively to one of them. They were also given the opportunity to write comments about their choices that might amplify their reasons for, and therefore the researcher's understanding of, their knowledge. The tasks were based on the researches of Wandersee (1983) and Kinchin (2000 (b)). They include students' naïve ideas in the following categories:

1. Structure and Function of Leaves;
2. Basic Biochemistry and Biophysics;
3. Energy Concepts;
4. Soil Concepts (related to energy intake).

Tasks 1 and 2 involved the first category, Tasks 3, 4 and 5 the second, Tasks 6, 7 and 8 the third and finally the last two Tasks, 9 and 10, the fourth category. Eight of the ten tasks were identical to those suggested by Kinchin, but Tasks 1 and 3 were new being based on two other common

misconceptions about the involvement of water in photosynthesis identified by Wandersee in which students hold the beliefs 'leaves take in water from the air' (Category 1) and 'plants change water into sugars' (Category 2)

Participants were also given the opportunity to write comments about their choices that might amplify their reasons for, and therefore the researcher's understanding of, their knowledge. The task design is shown below.

1. Structure and function of leaves (general)

1. Leaves take in water from the air	
A No Plant leaves need water for photosynthesis. The water is carried up through stems from the roots.	B Yes Leaves contain small holes, called stomata, which when it rains absorb water for photosynthesis. In addition, water vapour is taken in through these holes.
My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one) Reason for my choice	

Figure 4.16 Matched pairs test (after Kinchin)

The second set of pre-A level tasks consisted of questions that tested participants' understanding of the anatomical structure of leaves as well as the sub-microscopic detail of the chloroplast. It was basically a short written exercise.

4.5.2.2 Advanced-level tasks

These were intended to reveal participants' knowledge and understanding at the standard expected for the 16-18 age group studying A2 Biology for any of the specifications. The questions were a distillation from material found:

- in the CD-Roms;
- in A-level specifications;

- to be conceptually weak on photosynthetic topics as revealed in interviews and in response to examination answers from preliminary work involving A-level students and in analysis of past A-level answers.

The questions were designed to elicit more information on participants' knowledge than can be revealed by either simple yes, or no, or multiple choice, responses. However, it should be easy to administer and to mark. Several authors (Levine et al. 1970, Odom & Barrow 1995, Jones 2001) have criticised the multiple-choice test for a variety of reasons. Levine et al. (1970) for its failure to measure certain cognitive skills, Odom & Barrow (1991) its inadequacy in revealing understanding and Jones (2001) because, though it is reliable, it is an invalid instrument. Burton et al. (1991) show how difficult it is to write valid questions of this type. Indeed, a study undertaken by Wallace of students' understanding of concepts in marine biology reported in Wallace & Mintzes (1990) revealed how critical the choice of assessment measures could be, since a multiple-choice test revealed little change, but concept mapping and interviews suggested improved knowledge.

Nevertheless the format that was initially selected for the second part of the photosynthetic diagnostic test was the two-tier multiple-choice test as devised by Treagust & Haslam (1986), notwithstanding the previous comments since it has been used by a number of researchers, such as Odom & Barrow (1995) and most recently by Tsai & Chou (2002). In this test, each multiple-choice question is followed by a number of phrases, one of which supports the correct response, thereby giving greater insight into understanding than would the multiple-choice test alone.

Ten questions were set on each of the light-dependent and -independent reaction, an example of which on the light-dependent reaction is shown in Figure 4.17.

<p>(i) Light energy is initially</p> <p>A channelled to the reaction centre of the light harvesting units</p> <p>B converted into ATP</p> <p>C trapped in the antenna of light harvesting units</p> <p>D used to produce high energy electrons</p> <p>I have given my answer because</p> <p>the reaction centre must be the site where energy is used</p> <p>ATP is always made from sources of energy</p> <p>the antennae are on the surface of chloroplast membranes</p>
--

Figure 4.17 Example of a two-tier multiple-choice question

At an early stage in the Pilot the format of these questions as well as the content of some of them proved to be unsatisfactory for the reasons explained on p.131. Therefore a largely new set of questions in a different format was devised. These questions also covered the light-dependent and -independent stage, though their focus was on the light-dependent phase for reasons also discussed later (pp. 131-132). Questions were taken from past A-level papers, from some of the questions set in the previous test and from Photosynthesis: A Basic Biology Course (Tribe et al. 1975). They were of the multiple-choice variety, but there was, as before, an opportunity for responses to be followed by comments about the answers. However, unlike the previous questions, these comments were to be written down by the participants, rather than their making a selection from a number of options. One example of these questions is shown in Figure 4.18.

3. During photosynthesis, which process releases electrons that return chlorophyll molecules to their reduced state?

- A activation of photosystem 1
- B oxidation of reduced NADP
- C phosphorylation of ADP
- D photolysis of water

I have given my answer

Because I guessed

yes

no

Because _____

Figure 4.18 Revised two-tier multiple-choice question

There were thirty-two questions twenty-six of which represented items testing most aspects of photosynthesis and six testing problem solving skills linked to interpretation of data from photosynthetic experiments.

4.5.3 Participants

Seventeen students from Culford School, Bury St. Edmunds volunteered for the pilot. The School is a private institution, coeducational and with about 650 pupils of whom one-third are resident. The participating students were either fifth or sixth formers (years eleven, twelve or thirteen) and both boarding and day. These participants had all been taught biology by the researcher for at least one year. Most possessed the same educational backgrounds having entered the School in year seven. Only two participants had entered later in year twelve.

Ten of these participants (eight of whom are identified as Participants 1, 2, 3, 4, 5, 6, 14 and 15 in the *Photosynthesis Explorer* pilot)) were in the sixth form and are identified as pairs A, B, C and G in the *Photosynthesis Explorer* Pilot and the other pair is designated S in the *Discovering Science (Cells and Energy)* pilot. Pairs A, B and G together with Pair S that used *Discovering Science (Cells and Energy)* were in their final year of the sixth form studying biology (human). Of the seven General Certificate of Secondary Education (GCSE) students, four of them worked as pairs D and F (Participants 7, 8, 12 and 13) whilst the three remaining worked as a triad, E (Participants 9, 10 and 11).

All of the participants in the sixth form gained at least B grades in double award science at GCSE level. Two of them held double A* awards in science and one gained an A* award in biology. The remainder possessed A grades in either biology or double award science and only one (Participant 5) had a lower grade, B. All had studied physics and chemistry, either as separate subjects or as part of the double award. The seven GCSE participants were studying separate sciences and were predicted to gain at least an A grade in biology. None of the participants had been taught photosynthesis at a level beyond that of GCSE.

4.5.4 Audio, video and related equipment and research room set up

A flat bed tape recorder was used to obtain audio information during the periods that the participants worked at the computer. A Sony video camera, mounted on a tripod recorded all visual material relating to the research. A

monitor was also available as were mirrors, which were used to allow video recording of eye movements towards the display screen or keyboard, or away from both. The computer with screen was assembled on one bench together with a microphone and audio tape recorder. Behind the computer screen were placed the two mirrors and the video camera was placed on a tripod two metres from the screen in order to capture events on screen and in the mirrors. A television monitor was also available in order that the researcher could observe what was being recorded throughout.

4.6 Procedure (for the *Photosynthesis Explorer* program)

It was anticipated that the procedure, pre-test, software work and post-test would take two hours. Participants were asked to set aside at least this amount of time, either in the evening or at the weekend on days between March and May 2002. Pairs of participants, working as individuals, answered the pre-test exercises in a classroom immediately prior to working on the software. They were not permitted to confer about their answers. After completing the questionnaire, participants were asked to work through the program in pairs without any detailed instruction, other than to tell them that their objective was to learn about photosynthesis. When the program was started, the audio and video equipment was made operational and the participants' position at the computer adjusted so that facial expressions and head and eye movements were reflected in the mirrors for recording on video. Participants were asked to verbalise their ideas on questions asked in the program and to talk through their answers and to discuss them together or with the researcher.

At the end, the first two pairs of participants were asked individually to complete the A-level post-test questions on the light-dependent reaction only. Whilst the participants had free access to all parts of the program, in the two-hour period this was primarily, though not exclusively, what the participants had sought answers to.

Pairs of participants used the *Photosynthesis Explorer* program and only one pair worked through the *Cells and Energy* program.

4.7 Modified procedure (Phase 1)

Because of the observed participants' inability to map a route through the hypertext facilities on the *Photosynthesis Explorer* program, two modifications to this procedure were made after the first two pairs had completed their tasks. As a consequence, all participants after the first 2 pairs (A and B) were instructed to concentrate on the light-dependent reaction of photosynthesis and to use the program in the following order: First Look, Explorations and finally Core Enquiries.

4.8 Test findings from Pairs A and B

After the first two pairs had responded to the written tests, they were marked and evaluated for their suitability of use by future groups.

4.8.1 Pre-advanced level tasks

In the matching pairs tasks, these first four participants scored seven or more marks out of ten suggesting that there were very few of those misconceptions identified by Kinchin held by this group.

On the short written paper, participants wrote briefly on the functions of cells in plant leaves, though these were not analysed in terms of what Anderson & Sheldon (1990) called the 'goal concept' at this stage either. Nevertheless a brief search through their answers suggested that they all knew about the basic functions of specific cells in leaves, though not the detailed structure of chloroplasts, which was not topic covered in first year A-level work. As for the pre-A level test, this one remained unaltered, too.

4.8.2 Advanced-level test

As originally envisaged both the ten-question light-dependent and -independent test were to be used as pre- and post-test exercises. However, because of the extensive time (up to 5 hours) devoted both to answering the pre-test and post-test exercises and to working with the CD-Rom on the light-dependent reaction alone, the only post-test used was that on this topic. Each question was marked by giving it a single mark if the multiple choice item was correct and three marks if the correct accompanying statement was also recognised. The possible total mark was thirty. One participant from the first pair scored thirteen on the pre- test and an even lower one on the post-test (eleven), which was interesting, and the other scored six and then twelve. However, the second pair gained equal marks on the pre- and post-test: one scored nineteen and the other twenty. This second result gave rise to concern about the validity of the test, since participants here were scoring very high marks in the pre-test exercise on topics, such as that linked to the thylakoid membrane about which they could have known little. This was confirmed by the fact that in the short written answer section of the pre-test

they possessed no knowledge at all of photosystems or thylakoid membranes. It was also concluded that the reasons were to be found in the phrases that appeared after each question, which adds support to Griffard & Wandersee's (2001, p.1) reference to the invalidity of this instrument, since '*participants' verbal data indicated that they relied on test-taking strategies, not retrieval from memory*' and to the difficulties of setting questions with a multiple choice element (Burton et al. (1991). The phrases were likely to have guided participants to the correct response in the multiple-choice part. In other words, participants were using a legalistic process of elimination to find the correct answer, which failed to reveal anything about their understanding.

Since the test was judged to be invalid, it required either a careful re-writing of the phraseology, or a change in the format of the test. There was a real imperative to find an alternative quickly, since participants had made themselves available for several hours, mostly during weekends from March to May, before external examination pressures prevented them providing further assistance.

The new test had to provide more information than a multiple-choice test could, but it was essential that no clues were provided that might guide participants to the right answer. The solution to this was to offer them a space in which to write their reasons for their answer to a multiple-choice item.

4.9 Modified procedure (Phase 2)

After the analysis of Pre-A level tasks and the two-tier multiple-choice test for Pairs A and B, the effects of the changed instructions to the use of the *Photosynthesis Explorer* program were evaluated after a further two pairs had completed the assignments. This was necessary for two reasons. The first developed from the concern, already described, about the over-long, overall period of participant involvement and the second from the navigation strategy adopted by Pair D.

The first pair (Pair A) spent 150 minutes and Pair B 185 minutes using the Explorer CD-Rom. Pairs C and D spent rather less time 105 minutes and 80 minutes respectively, which was considered more manageable, but Pair D was particularly hampered in reaching any conclusions to the series of discovery exercises, since the members of the pair used the program to find out the answers to questions in the A-level pre-test. They became increasingly frustrated by their failure to find any, because the program did not deliver any answers at all, reflected in the comment made by one member of this pair:

'Do they never tell you if you get it right? They just ask questions. Shall we look for something else so that we can find stuff?'

In consequence, after 80 minutes they became very confused and gave up. It was, possibly, naive to expect participants to discover a strategy by which they could learn about photosynthesis using the materials available. The experience of observing Pair D suggested that when new material is being learnt a route map is, if not absolutely essential, useful in, at the very least, making effective progress through a program.

It was decided, therefore, to impose a structure to the participants' learning by providing verbal instructions as to how they might best use the program. The learning objective was to be that of the light-dependent reaction alone and the framework was based on the menus that were available in the program. At the start, they were to use First Look, which explained how to navigate through the program and to access the menus and sub-menus. Next, they were to go to Explorations and to look at in order the sections on 'What is Photosynthesis?' and 'Light: Introduction' to provide an overall briefing on the topic. Finally they were to go to Core Enquiries and work through the sections in the order:

- Reactants and Products: Introduction;
- Light and Photosynthesis: Overview;
- Photosynthetic Reactions: Light Reactions;
- Energy Storage: Energy Compounds;
- The Electrons: Introduction;
- Protons and Oxygen: The Protons.

Each section provided a logical framework in which to learn about a particular aspect of the light-dependent reaction. If, for example, section Reactants and Products was to be studied, there were ten separate pages to look at with the aim of 'discovering' the roles of water and carbon dioxide in photosynthesis. As well as the so-called work window in which participants were expected to carry out operations, there is as previously described a model window which may be in leaf or mechanisms mode demonstrating the effects on the leaf of changing certain parameters in terms of inputs, outputs and reactions within the thylakoids and stroma.

The bar chart (Figure 4.19) shows the time spent using the *Photosynthesis Explorer* software for Pairs A, B, C and D, as well as for all the other groups. The time spent on the software by these other groups ranged from 95-110 minutes, which was a large reduction on the 150 minutes and 185 minutes spent by the first two pairs.

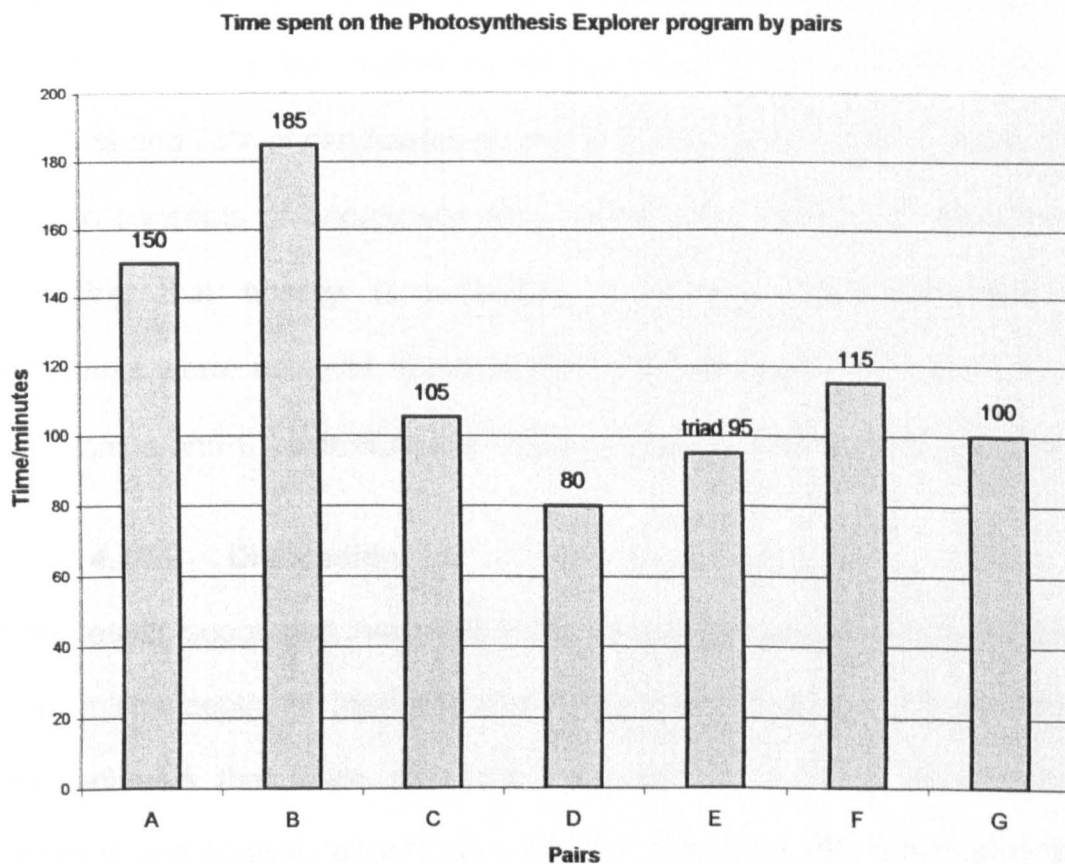


Figure 4.19 Bar chart of time spent on *Photosynthesis Explorer* program by six pairs and one triad

The rest of the results and discussion does not include the first two pairs, since changes had been made, not only to the way in which the software was used, but also to the A-level test used to provide one measure of their understanding about photosynthesis.

4.10 Findings from pre-A level matched pairs tests

4.10.1 Results (for all participants)

Most (80%) of participants were able to answer Questions 1 and 2 (on structure and function of leaves) correctly, whereas a higher percentage (87%) were confident that carbon dioxide as well as water contributed to sugar formation (Question 3). However only 60% gave the correct answer to Questions 4 and 5 that tested knowledge about photosynthetic products. 60%, 73% and 73% of candidates answered questions 6, 7 and 8, which were linked to concepts of energy correctly, with a large minority of participants suggesting that energy is produced in photosynthesis (Question 6). Participants were, however, more confident about energy in relation to soil (Questions 9 and 10) with 80% and 100% of them recording correct scores.

4.10.2 Discussion

These results suggested that participants in this Pilot Study possessed few of those misconceptions (derived from Questions 2 and 4 to 10) about photosynthesis that were highlighted by Kinchin from his observations, interviews and analysis of concept maps for students at the lower secondary level in British schools. There are many possible explanations for this initial finding, which might relate either to the test's design and the language used, making it inadequate to inquire into these misconceptions, or to the possible reduction in these misconceptions in older students. The two new questions that were introduced (Questions 1 and 3) that highlighted two additional misconceptions (reported from Wandersee's seminal work using elementary and high school students as well as college sophomores) showed overall correct responses (80% and 87%) similar to the pattern established for the

other eight (range 60-100%). Again, it could be suggested that this is because either these questions were unable to adequately probe participants understanding due to the inadequacy of question design or the language used, or because of the sound conceptual understanding of this group of students on these two concepts investigated. However, in Wandersee's study only between 32% and 38% of the students knew the answer to the concept of water vapour exchange in leaves, even in the sophomore group, whereas in the Pilot 80% did so. This is too large a difference to ignore. However, it would not be possible to consider statistical differences between the responses, since the questions asked were different, as was the educational background of the students and, in the present study, the participants were self-selected because they were volunteers and the sample size was very small.

Nevertheless the results for all the questions, whichever way they are viewed, either by question or by participant are consistent. Only one participant could be considered as an outlier, with a score of 3 out of 10, but he was academically weaker than the rest, with a B grade in double award science, four other Bs and five grade Cs. It does perhaps appear from this small sample that most participants in the Pilot brought with them relatively few pre-A level misconceptions about photosynthesis at the start.

4.11 Findings from pre-A level short written answer test

4.11.1 Results

Participants' answers were very varied in depth, length and content, but were for the most part very superficial. They wrote briefly on the general function of

cells in plant leaves. However, it was immediately obvious, because of the variety of responses, that a detailed analysis was a very complex task. Therefore, no attempt was made to analyse them in detail, but two features were apparent. All participants:

- possessed sound recall on leaf morphology;
- knew nothing about detailed chloroplast structure.

4.11.2 Discussion

The answers to these questions provided few comments to assist in gaining insights into participants' understanding. It was judged that their detailed analysis was likely to be very debatable, since the questions were open ended, which allowed participants to answer them with different foci. As noted in the results two broad findings were apparent, the second of which was used to provide evidence for the modification of the Advanced-level test (subsection 4.8.2).

4.12 Findings from A-level questions for Pairs C, D, F, G and Triad E

4.12.1 Introduction

Every answer, for each participant, to the pre- and post-test A-level questions was awarded a mark only if correct, other than for Question 23, no matter what was written in the response section. Question 23 had two correct responses and participants were awarded one mark if both were correct and a half mark if only one was correct. The data were then analysed statistically by the use of a non-parametric test, the Wilcoxon signed rank test, to compare participants' pre- and post-test scores.

4.12.2 Results

A summary of the overall results for the 32 questions is shown in Table 4.6. Since, as outlined on p. 134, there were more specific instructions given to Participants 9-15 than to the pairs who came before them, responses to the tests have been divided into two groups. It is important to reiterate the changes made once again. The first group, consisting of Pairs C and D were neither provided with a specific learning objective (other than to find out about the light-dependent reaction of photosynthesis) nor a strategy by which they might use the CD-Rom more effectively. The remaining pairs and one triad (F, G and triad E) were told to focus on the light-dependent reaction and to work through the program using the sections in the order First Look, Core Enquiries and Explorations, within which they were to tackle the first six sub-sections from Reactants and Products to Protons and Oxygen.

Number of correct responses out of 32											
Group without specific learning objective and strategy						Group with specific learning objective and strategy					
Pairs						Pairs					
C		D		E*		F		G			
Participants						Participants					
	5	6	7	8	9	10	11	12	13	14	15
Post-test score	7.0	13.5	7.0	4.5	14.5	14.5	15.5	13.5	12.5	11.0	9.5
Pre-test score	8.0	13.5	12.5	11.5	8.5	5.5	10.0	8.5	2.5	7.0	4.5
Difference	-1.0	0.0	-5.5	-7.0	6.0	9.0	5.0	5.0	10.0	4.0	5.0

Table 4.6 Summary results of the pre-test and post-test exercises
Half a mark was awarded for one of the two alternative correct responses to one of the questions (Question 4) * Triad

When the results of the pre- and post-tests are compared there are differences between the two groups. As shown in Table 4.6, as a consequence of an analysis of the pre- and post-test questionnaires,

participants without specific learning objectives appeared to know less about photosynthesis after using the program than they did before. However, when participants were given clear guidance and a strategy their performance on the post-test actually improved. Table 4.7 shows the extent of this improvement in percentage terms. Pairs C and D had 11.5% fewer correct responses on the post-test than on the pre-test whereas the situation was turned around when more precise instructions were given. Here there was an improvement of 19.2% between the outcomes of the group with and the group without a specific learning objective.

	Percentage of correct responses	
	Group without specific learning objective and strategy	Group with specific learning objective and strategy
Post-test	25.0	40.0
Pre-test	35.5	20.8
Difference	-11.5	+19.2

Table 4.7 Overall percentage change in performance of two groups with and without objectives and strategy

4.12.3 Statistical analysis

When the Wilcoxon test was undertaken on the pre- and post-test scores for those given no guidance, using a non-directional (2-tailed) test the probability was $P > 0.05$ ($P = 0.109$), which is not significant. so the null hypothesis applies. Nevertheless all the results were in the same direction, which is that all the participants scored lower marks in the post-test. When the same test was used on the pre- and post-test scores for those given guidance $P < 0.05$ ($P = 0.018$). This allowed the null hypothesis to be rejected. There was a

statistically significant difference between the participants' performance in the test questions before and after the use of the program. Since the test questions were mainly on aspects of knowledge and understanding about the light-dependent reaction these results suggested that there was a significant improvement in knowledge about the light-dependent reaction when these participants used *Photosynthesis Explorer*.

4.12.4 Analysis of pre- and post-test question results

Tables 4.8 and 4.9 show the gains and losses in those questions that were considered worth highlighting later in the discussion stage, since these showed at least two mark differences between the pre- and post-test stages with at least 50% of participants achieving the right response in the post-test providing some comparability (since group sizes were different) and measure of overall group achievement. It was important to hold on to a difference of at least this size, since there was evidence of guessing, especially for Participants 5-8, where twenty-two correct responses were made to questions in the pre-test, but these were not repeated in the post-test. This was less evident in the other group with only twelve changes of this kind.

A loss of two or more marks whatever the group was judged as a decline in overall score, regardless of the size of the group.

Questions increasing by two or more marks on post-test (Participants 9-15)				
Question number	Skills tested	Stage of photosynthesis	Question focus	Difference in score
3	Knowledge, recall and understanding (KRU)	Light-dependent reaction	Photolysis (meaning of)	+4
9			Photolysis (products of)	+3
13			Photolysis (heavy isotopes and oxygen)	+3
18			Products of LDR (named)	+2
24			Products of LDR	+3
26		Link reaction	Link chemicals per se	+5
27			Link chemicals + LDR and LIR chemicals	+5
15		Unclassified	Compensation point	+2
23		Chl/plast function	Sites of LDR and LIR in chloroplast	+6
5	Data analysis graph (DA)	Light-dependent reaction	Rate of photosynthesis and wavelength	+2
33		Integrated	Deducing events in photosynthesis	+4
Questions decreasing by two or more marks on post-test (participants 9-15)				
7	KRU	Light-dependent reaction	Excitation of electrons in chlorophyll (a)	-3
21			Proton movement during electron movement	-2

Table 4.8 Summary of main gains and losses in post-A level test (compared to pre-test) for Participants 9-15

Questions increasing by two or more marks on post-test (Participants 5-8)				
Question number	Skills tested	Stage of photosynthesis	Question focus	Difference in score
27	KRU	Link reaction	Link chemicals + LDR and LIR chemicals	+2
Questions decreasing by two or more marks on post-test (Participantss 5-8)				
10	KRU	Light - dependent reaction	Acceptor molecules in thylakoids	-2
12			Photolysis in isolated chloroplasts	-2
18			Products of LDR (named)	-2
24			Products of LDR	-2
25	KRU	Chl/plast function	Sites in chloroplast of e.g. light absorption	-3
33	DA		Deducing events in photosynthesis	-2

Table 4.9 Summary of main gains and losses post-A level test (compared to pre-test) for Participants 5-8

For Participants 9-15, gains (more than 2 with 50% or more of them answering correctly) were made to eleven questions out of thirty-two, with all of these (except one graphical data analysis question) being answered

correctly by more than half of them. These questions related to photolysis, to the products of the light-dependent reaction to chemicals that linked the light-dependent and -independent reaction and to compensation points. In addition, analytical questions that involved graphical information improved, too. Two questions, 7 and 21, scored less well on the post-test. These related to electron excitation and proton movements.

Participants 5-8 showed an improvement in response to one question only, Question 27 that involved link reaction chemicals. Six questions received a lower score on the post-test, though no pattern emerged in the responses made.

4.12.5 Discussion

With regard to Participants 9-15, whilst there might well be some guessing as to the correct responses, many of the areas that might be expected to improve did so, especially those that related photolysis to the products of the light-dependent reaction and to chemicals that linked the light-dependent and -independent reaction, since these were clearly defined and emphasised in the program. Questions that showed no improvement could also be explained because of weaknesses in the program or because there was nothing in it relating to this topic. Responses to Question 7, which was about light energy, chlorophyll, electrons and their transfer, and to Question 21, which was related to proton movement in relation to the thylakoid membrane, probably reflected modelling weaknesses, which are discussed further on pp. 152-153.

With regard to Participants 5-8, the results are probably explicable in terms of the lack of focus when working on the topic within the program.

The results with Participants 9-15 gave some confidence to the view that the program was having effects on participants' outcome with regard to understanding about photosynthesis, at least in terms of their ability to answer questions of the multiple choice variety.

However, the discussion above considered the topic cover of the questions and the accuracy with which they were, in some cases, written. In addition, there was some evidence of guessing. The final point about these questions that needed to be considered at this stage was the fact that they were supposed to provide additional evidence of participant understanding through their written comments. This was simply not done by any of them to any great extent and therefore a new form of test needed to be explored before the Main Study commenced.

4.13 Audio analysis

4.13.1 Introduction

The value of discourse in delivering a change of behaviour has been discussed (see p. 54). The following qualitative analysis was to enable the possibility of emergent hypotheses to be developed: it was 'grounded' on the data generated by the research (Glaser & Strauss 1967).

A variety of participant activities whilst at the keyboard are important in determining those processes that might lead to success or failure in learning about specific subject matter. These will include manual activities, such as operations at the keyboard and of the mouse, verbal cues, as well as periods of contemplation and reflection.

Therefore, the first stage was to categorise the events as they emerged from a complete transcript from one of the group's discourse and the second was to:

- produce overall times that participants spent on these categories;
- see if the more clearly defined procedure for pairs F and G and triad E made a difference to the duration of each of these activities, particularly the degree of discourse.

The initial categories were: talk on photosynthesis, talk on the program, keyboard activity and teacher intervention, with a residual category of silence. Next all the discourse events that involved participant talk and teacher intervention were split into eight discrete categories that not only related to the test questions, but also to events in the light-dependent reaction as developed in the program. One other category was included, that of organic chemical synthesis, since the multiple-choice test included one question on that topic.

The nine categories were

- photolysis
- electron transfer to chlorophyll (a)
- photosystems I and II and general membrane function
- reduced NADP and ATP synthesis
- link reaction
- electron flow and reduced NADP synthesis
- proton flow and ATP synthesis
- thylakoid and stromal functions
- organic chemical synthesis.

The next stage was to note from the audio-tapes instances of learning, misconceptions, difficulties (that were either remedied by participant

discussion or by teacher intervention) and remedial action taken (with or without difficulties being expressed) for each of these eight categories.

4.13.2 Results (duration of events at the keyboard)

Group	Percentage of time spent on each activity				
	Silence	Talk on photo-synthesis	Talk on program	Keyboard activity	Teacher inter-vention
Without specific learning objective and strategy	56	20	5	6	13
SD	12.5	8.6	5.3	4.1	9.9
With specific learning objective and strategy	62	23	4	6	6
SD	10.6	11.1	4.5	3.5	1.0

Table 4.10 Overall percentage time spent on each activity by group during operation of the program

Table 4.10 shows the proportion of time spent on each of the categorised activities. Irrespective of the group, the majority of time was spent in silence, though around 20% involved participant talk on photosynthesis. Participants spent relatively short periods on talk involved with the use of the program (use of icons, hypertext and zeroing variables when using simulations for example) and on keyboard activity. The overall duration of teacher intervention was also short, but was reduced from 13% to 6% when an introduction was provided with clear learning objectives and strategy.

4.13.3 Discussion

The findings suggest that the *Photosynthesis Explorer* program when used by groups generated considerable discourse. Around 30% of the time was devoted to talk, either between individual participants, or between them and

the researcher. This was considered to be worth further analysis to investigate the nature of the discourse. However, the audio-tape could not help in developing any insights into what happened during the long periods of silence or even the shorter periods of keyboard activity. These deficiencies have clear implications for the Main Study, which would require some means of recording what was happening during these long, silent periods.

4.13.4 Results (discourse events)

Categories	Number of events that			Required Remedial action
	Learning	Difficulties	Misconceptions	
Photolysis	9	2	11	5
Electron transfer to chlorophyll a	0	1	0	0
Photosystems I and II and membrane function	0	6	0	6
Reduced NADP and ATP synthesis	4	1	5	1
Link reaction	4	1	0	1
Electron flow and reduced NADP synthesis	2	0	1	5
Proton flow and ATP synthesis	3	0	0	4
Chloroplast thylakoid and stromal functions	4	6	1	2
Organic chemical synthesis	2	0	1	0

Table 4.11 Number of discourse events for Groups C-G (Participants 5-15) that show learning, difficulties, misconceptions and dialogue illustrating remediation

The audio tape data (Table 4.11) illustrate a number of learning events most particularly on photolysis (9), the synthesis of reduced NADP and ATP(4), the linking chemicals between the light-dependent and -independent reaction (4) and thylakoid and stromal functions (4). For example, specific learning events

related to photolysis are shown by the first two comments under 'Specific Participant Comment' in Table 4.12.

Knowledge and Understanding	
Theme	Specific Participant Comment
Light-dependent reaction	'The source of oxygen is water' 'Water is split into oxygen, protons and electrons' 'Water participates directly in the light -dependent reaction' 'Oxygen production, ATP, NADPH + H ⁺ are dependent on light' 'Electrons are directly involved in NADPH + H ⁺ production'
Light-independent reaction	'Carbon dioxide participates directly in sugar production'
Links	'The light-dependent and -independent reactions are linked by ATP and NADPH + H ⁺ '
Chloroplast structure and function	'Chloroplast membranes (thylakoids) are involved in the splitting of water' 'Chloroplasts have stroma and thylakoids'

Table 4.12 Examples of learning and understanding developed during participant discourse

In addition, however, for each of these categorised learning events within the groups there were also either misconceptions or difficulties and sometimes a need for their resolution by researcher intervention (remedial action). Some specific participant comments illustrating participant misconception are shown in the six statements below:

- 1) NADP causes water to split;
- 2) Carbon dioxide is the source of oxygen;
- 3) Sugars provide energy for photosynthesis;
- 4) Carbon dioxide is not converted to sugars by chloroplasts;
- 5) Blocking electron flow should not make any difference to oxygen or to ATP production;
- 6) Production of high-energy compounds does not depend on light.

The first two statements relate to misconceptions and photolysis and the second of these probably arises from a difficulty with Core Enquiries right at

the outset (see Figure 4.12, Light reaction – making a prediction). A development of these issues is to be found in the discussion section below.

There are a number of other difficulties, other than technical ones, that may be resolved by teacher intervention. The specific ones discovered from the participant narratives in this Pilot are illustrated in Table 4.13 below.

Difficulties	Specific Weaknesses
Questions	Questions are sometimes misleading and importantly so. For example right at the outset participants are very muddled about atoms and molecules with regard to carbon dioxide and water. In addition a question on chloroplast membranes directs participants to conclude that sugars are not made in the chloroplasts at all
Modelling	<p>Structure of chloroplast lacks detail of the thylakoid membranes, chlorophyll and PS1 and 2</p> <p>There is insufficient focus on the importance of light in the model</p> <p>Chemical names, although some of them are given a hypertext, are insufficient to describe their nature and importance</p> <p>Movement of protons and electrons is unclear</p>

Table 4.13 Specific difficulties (excluding those associated with navigation through the program) restricting learning

4.13.5 Discussion

At the outset, it is, perhaps, important to provide some explanation for the numbers found in each row (Table 4.11). If the first category is selected, that of photolysis, discourse very clearly provided learning events, but also this discourse provided evidence of misconceptions some of which necessitated remedial action, since it might have detracted from participant understanding later on. This discourse may or may not have eliminated these misconceptions as is discussed further below.

In the discussion below, the focus will be on photolysis, since the learning that appeared to take place, the difficulties noted, the misconceptions revealed

and the remedial actions taken clearly illustrate a number of drawbacks with this program. However, mention will also be made relating to other learning events involved with thylakoid membranes and to specific problems associated with these.

Participant discourse illustrated learning events about photolysis (9 in total), but also difficulties (2) and misconceptions (11) some of which were resolved by remedial action (5). It was unfortunate that such problems occurred during an early part of Core Enquiries. A diagrammatic representation of the Work Window page 3 will illustrate the point.

CORE ENQUIRIES: Reactants and Products: What goes where? (Work Window page 3)

Given that the basic formula for all sugars is CH_2O , draw arrows to show where you think each atom of the reactants might end up in the products.

(Click inside the large area to activate the drawing tools.)

*In your diagram, which atoms have only one possible destination?
For which ones are there multiple possibilities?*

Figure 4.20 Core Enquiries – reactants and products - Work Window

Participants did not see much of a problem with the task or question. Most of them incorrectly concluded that carbon dioxide was the source of oxygen and

that water together with carbon formed the carbohydrate. There were, therefore no multiple possibilities. The simulation that followed revealed that the oxygen did indeed originate from water. However, the damage was already done for some. A number of participants accepted the evidence; others did as a result of discussion with the researcher, though others did not. Thus statements such as 'Some oxygen comes from carbon dioxide and the rest from water' or 'We were told that the oxygen comes from water ' sounded very unconvincing indeed.

Other problems generally developed either from misunderstanding descriptions about chloroplast membranes, from the model of the thylakoids or from the reactions involved in the stroma and thylakoids using the Mechanisms Window. One of these puts at risk an understanding of the chloroplast itself, since in Core Enquiries participants are asked about the Hill reaction in the following way.

CORE ENQUIRIES: **Photosynthetic Reactions: Light Reactions (p. 1)**

In 1937, the British scientist R. Hill found that isolated chloroplast membranes release oxygen in the light, but do not convert CO₂ into sugar.

What conclusion can you draw from this result?

At first sight there was no problem with this question, but participants tended to read for chloroplast membrane, simply chloroplast, thus they lost the whole point about the question. Indeed, one participant stated that 'Carbon dioxide is not converted to sugars by chloroplasts' (see p.158). It was necessary for

the researcher to point out that chloroplast membranes are the same as thylakoids.

Finally, participants found great difficulty in answering questions about electron and proton flow and about membrane function generally. In the Core Enquiries sections called Energy Storage, Electrons, Protons and Oxygen close observation of the Mechanisms Window was essential for the correct interpretation of the events during simulation exercises. However even close observation of the flow of electrons and protons did not enable participants to arrive at the expected conclusion that $\text{NADPH} + \text{H}^+$ production is directly dependent on electron flow and that ATP is only indirectly so.

Comments on this by two participants suggest how some of them were way off the point in terms of energy and energy transfer with misconception comments such as 'Production of high energy compounds does not depend on light', 'Sugars provide energy for photosynthesis' and 'Blocking electron flow should not make any difference to oxygen or ATP production'. Whilst Table 4.11 in the categories Electron Flow and Proton Flow suggests that participants did not experience difficulty with this part of the program and that learning took place, this was only due to considerable researcher intervention. The screen dump (Figure 4.21) illustrates just how unsatisfactory the thylakoid model was in helping participants to understand the mechanisms involved with both the synthesis of ATP and reduced NADP.

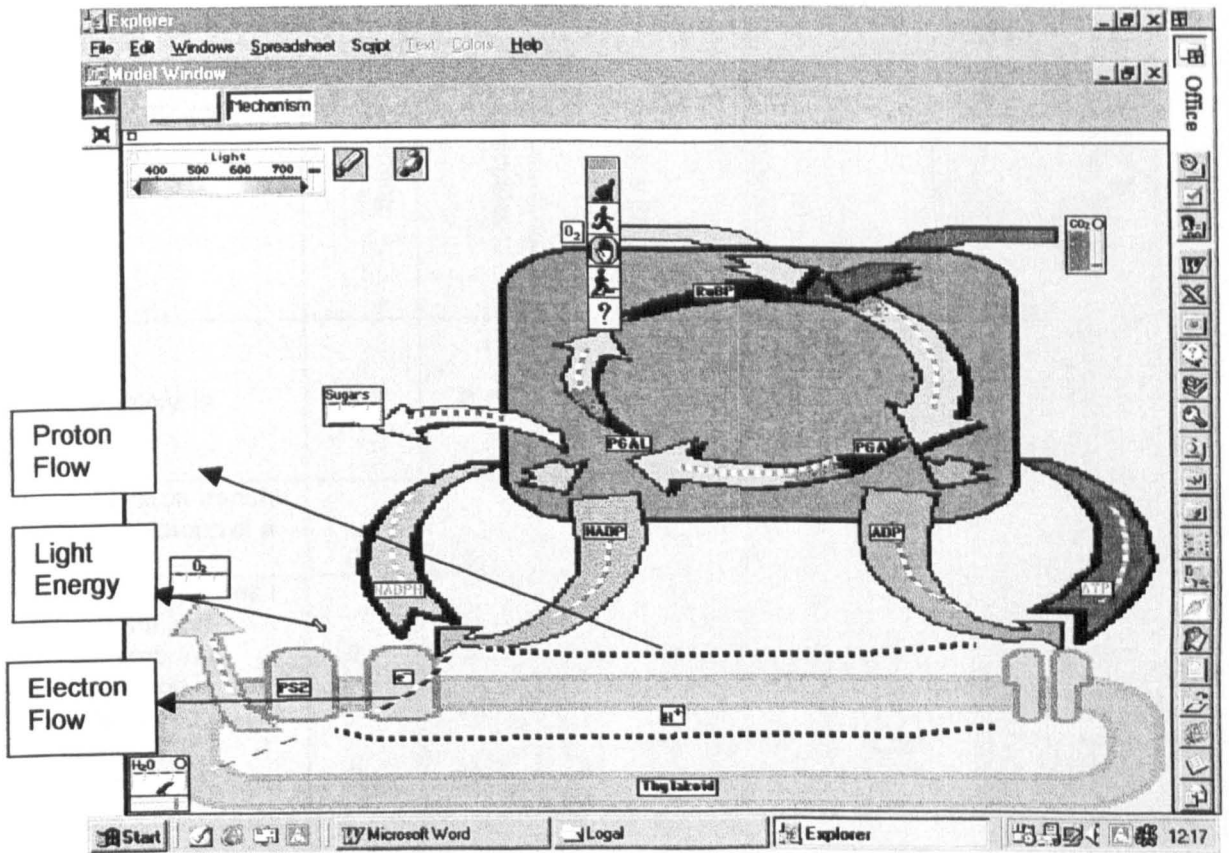


Figure 4.21 Mechanisms Window showing a thylakoid and stroma

The light arrow is hardly visible, the hypertext for the photosystems (PS2 illustrated) is poor and the movement of electrons from water to the photosystems is unclear as is the movement of protons from the thylakoid lumen to the stroma through the ATPase.

4.14 Results of discourse and test results compared

Generally participants made substantial progress on learning about photolysis from the *Photosynthesis Explorer* program as shown by the results of the post-test exercise. This was supported by the learning events noted in the discourse (Table 4.14). It could also be suggested that more progress might have been made had there been fewer misconceptions developed as a result of weaknesses in the program as previously noted.

4.14 Results of discourse and test results compared

Categories	Number of events that			Required Remedial action	Test Questions	
	Revealed Learning	Difficulties	Misconceptions		Test number on each topic	Change in response on post-test
Photolysis	9	0	6	3	(3) (9) (11) (12) (13)	+4 +3 +2 +1 +3
Electron transfer to chlorophyll a	0	0	0	0	(7) (8)	-3 -
Photosystems I and II and membrane function	0	3	0	3	(4)	+½
Reduced NADP and ATP synthesis	2	0	5	0	(16) (18) (24)	+1 +2 +3
Link reaction	3	1	0	1	(26) (27) (28)	+5 +5 +1
Electron flow and reduced NADP synthesis	1	0	1	3	(17)	+1
Proton flow and ATP synthesis	2	0	0	2	(21) (22)	-2 +1
Chloroplast thylakoid and stromal functions	4	5	1	1	(23)	+6
Organic chemical synthesis	0	0	1	0	(29)	-

Table 4.14 Comparison of learning, difficulties, misconceptions and remedial action with test responses for Groups E-G (Participants 9-15)

In relation to the second category, there was a real problem for participants' understanding in relation to light energy and electron transfer and photosynthesis. The program really did not address these issues at all, consequently there was no discussion about them and many participants lost

track of the source of energy for photosynthesis. It was hardly surprising that participants failed to progress in this area at all. Overall marks in the post-test either remained the same or actually fell.

Photosystems and membrane function were also poorly understood, with very little progress made in the post-test exercise. Whilst remedial action was attempted, because of the poor representation of the photosystems in the Mechanisms Window, from the evidence available from the audio-tape and post-test this did not apparently assist participants.

Participants appeared to have learnt that the products of the light-dependent reaction are reduced NADP and ATP and this was supported by participant discourse. It was also supported by their responses in the program itself, but this evidence was not recorded, which was a deficiency that needed to be addressed in the Main Study. The link reaction appeared to be the most clearly understood topic of all. Two of the questions on this topic produced 5 or more correct responses out of a maximum 7 from a very low base of either 0 or 1 in the pre-test. The audio analysis suggested that there were no misconceptions about it and very few difficulties. Post-test answers linked to electron and proton flow showed little if any improvement on those of the pre-test. The reasons for this have already been outlined.

Participants appeared confident about the functions of the thylakoid membranes and stroma, but only in terms of the location of the light-dependent and -independent reaction. There were a relatively large number of difficulties expressed, though these were not about the location of these

two parts of photosynthesis. They were, as already outlined, not about the reactions per se, but about the activities within the thylakoid itself.

4.15 Video analysis

Not all the participants' activities whilst working at the computer could be accessed from the audio-tape. It was considered appropriate, therefore that a more complete picture of other events, including additional insights into participants' knowledge and understanding, as revealed through a visual display, should be available whilst they were working at the computer. This was attempted using the video-tape in order to provide additional evidence for participant change in understanding as revealed in the written tests.

One of the tapes was run to find out if information on participant behaviour, including operation of the mouse, and eye or head movements or any other observable behaviour could be used to make sense of the time (greater than 50%) when nothing was recorded on the audio tape. In addition, as has already been touched on, operations at the keyboard were noted, but not the information actually being recorded on screen during these operations.

The only material in the video that showed clear resolution was the reflected view of the participants' faces. However, their head movements were such that their faces were not always in view. What seemed more important in the present study in terms of participant understanding were the manual actions performed by the participants as well as the results of such actions. Unfortunately the resolution of the image and on screen flicker made it very difficult to see what their responses were. Another method of on-screen recording was required.

4.16 Overview of the procedures used for the *Cells and Energy* program

The procedures used during the operation of the Discovering Science (*Cells and Energy*) program were similar to those used for *Photosynthesis Explorer*. The initial instructions were of a general nature. In brief, participants were told to find out about the light-dependent reaction of photosynthesis, which was the same instruction given to the later pairs using *Photosynthesis Explorer*. Only two participants (Pair S) took part in the Pilot after the other pairs had completed their work with *Photosynthesis Explorer*. However, as a consequence of the provisional findings on the questions set from this part of the Pilot and fully discussed in sub-section 4.12.5, it was important to trial a set of tasks at A-level that took on a different format, which would not only be more precisely focused, but also might deliver more participant written support for their choices. As a result of the *Photosynthesis Explorer* trial, the focus needed to be on the light-dependent reaction alone. Also it was important to include only tasks that tested knowledge and understanding rather than skills of data interpretation as well. This was for one main reason. Although *Photosynthesis Explorer* is essentially a simulations program with graphical data derived from actual experiments, directing the user to generate hypotheses and to make deductions about photosynthesis, this research is directed toward changes in conceptual understanding, rather than on the development of skills normally associated with simulation programs.

Because the pre-A level tasks had covered a wide range of topics on photosynthesis that Wandersee and others had considered weaknesses, it was decided to include only those from these tasks that addressed

misconceptions related to energy and photosynthesis and to supplement them with others that addressed light trapping and energy transfer. These were based on the work of Wandersee and Kinchin and from preliminary studies as well as from personal experience in teaching the topic.

At A-level, the task format was identical to that for pre-A level. In summary, there was an introductory statement, followed by two contrasting comments on this, with the participants expected to indicate in a box their agreement with either of these comment in respect of the original statement. There was a space also for a written comment.

The Task Booklet produced contained eight tasks at pre-A level and fifteen at A-level (Appendix B).

4.16.1 Results and discussion

Each of the tasks was awarded a single mark if correct and zero if wrong. The total for the pre-A level tasks was eight and at A-level fifteen.

The two participants produced similar marks for the Pre-A level tasks. Responses suggested both a sound knowledge of the basic concepts associated with energy and the role of plants in transforming it into other forms and, since the test was repeated after the use of the program, consistency in knowledge and understanding. One participant gained 6 marks in the tasks at both stages and the other one scored 7.

On the A-level tasks, both participants improved their scores after the use of the program. The participant who scored 6 in the pre-A level tasks scored 4

and 9 respectively in the pre- and post-A level tests and the other one improved by 6 marks from 3 to 9. In addition, just under half of the responses were supported by written comment.

The pair spent 73 minutes at the computer, but only 25 minutes of this was on photosynthesis itself. During this 25-minute period, the majority of it (59%) involved talk on photosynthesis the rest included 31% silence, 9% voice introduction to photosynthesis and only 1% intervention.

Compared to *Photosynthesis Explorer* the period of participant talk (59%) represents an almost threefold increase in the proportion of time spent on participant discourse. The period of silence was proportionately small (31%) as compared to 58% for *Photosynthesis Explorer* and teacher intervention was negligible (1%) as compared to 10%. There was no keyboard activity, since all operations could be completed with the mouse.

The profile of events when this program was used contrasts quite sharply with the *Photosynthesis Explorer* operation. The prolonged period of participant discourse was possibly caused by the need to obtain correct answers to questions before further progress could be made.

4.17 Overall conclusions from Pilot

The Pilot results suggested that participants might indeed gain knowledge about the light-dependent reaction of photosynthesis when using the *Photosynthesis Explorer* program, though only if they were provided with a

route to follow. Open-ended discovery appeared to be ineffective, as was partial guidance when using the program. What appeared to be more productive was a much more guided approach where specific instruction was provided at the start. The limited evidence from the Pilot about the Discovering Science (*Cells and Energy*) program supported the experience of OU tutors that this program is an effective tool.

4.18 Evaluation of procedures to inform the Main Study

The Pilot provided markers for undertaking the Main Study in relation to the:

- 1) most appropriate way to use the *Photosynthesis Explorer* program so that it was effective in promoting change, but which differed from the Discovering Science (*Cells and Energy*) in two fundamental respects: learning was promoted through experimental simulations and it carried few if any feedback opportunities;
- 2) specific aspect of photosynthesis for study;
- 3) administration and format and content of the tests/tasks.

It also confirmed that the information gained from the audiotape was sufficient for the researcher to recognise specific events, such as the discourse between participants and between them and the researcher. It could also inform whether this discourse between participants was supportive of each other's ideas or whether there was dissonance between a pair.

The video carried a backup to the audio material and more importantly a visual impression of what the participants were doing on-screen during this discourse, since the use of demonstrative pronouns by participants, such as

this and that, could only be interpreted with recourse to what was happening on-screen. Indeed the video could be used instead of the audio material, since it combined both audio and video recording. However, the video was deficient in one important respect, which was that although the general on-screen events could be recognised, the detail was not visually clear. Most particularly, words were not clearly defined, so that specific participant responses to the frequent questions that were asked in the program could not be read.

The Pilot suggested that in the Main Study.

- 1) Participants would be told what they were required to find out about photosynthesis using specific instructions. They would also be told which part of the program they were to use and in the case of *Photosynthesis Explorer* in which order this was to be done. In addition, they would be given assistance at particular points in the program that the Pilot had highlighted as being problematic.
- 2) The specific aspect of photosynthesis would be the light-dependent reaction. Although there are essentially two main parts to photosynthesis, the light-dependent and -independent reaction, time would be a factor in restricting the study. In addition, there are sufficient concepts about the light-dependent reaction in both programs that tests could be devised to quantify changes in knowledge and understanding.

3) The pre-A level matched pairs tasks would be used, since they did not appear to raise any problems for participants. There was, therefore, no reason to change it for the Main Study. However, since the research was to investigate participant knowledge and understanding about the light-dependent reaction, then knowledge and understanding about light, energy and photosynthesis were considered to be more relevant to the final study than the general questions used in the pilot. Though the modified A-level tests used in the *Photosynthesis Explorer* Pilot provided no more information about student knowledge than a multiple-choice test, some confidence in the test focus of the questions could be deduced from two sources:

- only those topics covered explicitly in the program showed marked improvement;
- participant talk revealed that these were the topics discussed and to an extent understood.

4) The A-level tasks would also take the matched pairs format not only for continuity, but also because it immediately followed the pre-A level test, which should provide participants with confidence about answering this kind of test question. Finally, it should enable participants to write comments about their choices, as was demonstrated in the *Discovering Science (Cells and Energy)* trial. Before this test was to be developed further (and indeed a pre-A level test) two narratives were to be written that would include the major aspects about energy and its involvement in the process of photosynthesis at the pre- and post A-level stages.

However, two questions were asked about the short written test. 'What purpose would this test serve in the Main Study?' and 'Would the data be impoverished in any way if it were omitted?' These questions were especially pertinent since not only were the tests very time-consuming, but this test would require very careful analysis of prose.

In answer to the first question, 'If it was to be used as a control to compare the pairs of participants using different pieces of software, then it was not appropriate, since whatever the method of prose analysis used it would be open to criticism'. In answer to the second, 'It is possible that lack of knowledge about leaf structure might restrict development of new knowledge, but not only would a more objective test be more reliable, but also could be constructed to reveal more pertinent questions about misconceptions related to the process of photosynthesis itself'. These features could be provided by the matched pair test alone as described above.

5) The scores in the A-level pre-test for the groups that used the different programs would be as far as possible equivalent. The difference in participants' scores on the pre-test at A-level when *Photosynthesis Explorer* was used (a) with and (b) without initial instruction compromised control. If a similar situation were to occur in the Main Study, with the knowledge and understanding of one group using one program being significantly different from the other, then this could invalidate any conclusions. It would be best in the Main Study to test all participants beforehand and if necessary assign them with some equivalence to either *Photosynthesis Explorer* or *Discovering*

Science (*Cells and Energy*) so that on that measure there would be little or no difference between the participants using the two programs.

The Pilot therefore provided data that informed the Main Study. The operation of the *Photosynthesis Explorer* program could be used by participants to learn about photosynthesis, but is it more or less effective than *Discovering Science (Cells and Energy)* and, if so, why?

One measure of effectiveness is the end product of this learning process. The Pilot suggested that the matched pairs test is likely to supply a rich source of both numerical and written data on which to make judgements about the extent of this learning. However the value of the two programs as resources for learning may also be investigated using cognitive walkthroughs, so that, for example, the value of feedback, interactivity and simulations of practical exercises may be explored as well as the need for and value of researcher intervention. The Pilot has provided useful signposts as to the way in which these data are to be collected, recorded and analysed in the Main Study.

Nevertheless there were still two main issues that needed to be resolved before data collection could commence. The first of these related to the exact content and format of the tasks and the second to the collection of on-screen data. Both of these will be addressed in the next Chapter.

Chapter 5 Main Study with statistical overview

5.1 Introduction

The Pilot Study enabled the selection of two contrasting multimedia programs that could be used to learn about the light-dependent reaction of photosynthesis. One of them *Photosynthesis Explorer* was rigorously trialled in order to explore how this program could be used to compare the effect of two types of software and with different levels of feedback. One of the principle findings of the Pilot was that in order to provide for a meaningful study to compare the two, a route had to be provided that enabled participants to follow a logical sequence through the menus provided on screen in this program.

This chapter develops answers to two questions posed as a result of the Pilot, which required resolution before the Main Study commenced. How was a clear record of the activities on-screen to be made and what was the final form of the test to be?

Second, the chapter not only describes the procedures used, but also provides an overarching comparison of the test results and time working at the computer, in which the two programs, *Photosynthesis Explorer* and *Cells and Energy*, are operated by different groups of participants.

The methodology used in the Main Study was in all essentials the same as for the Pilot. It was quasi-experimental and the conclusions reached were dependent both on statistical evidence and various forms of non-numerical data, including participant written and oral comment.

5.2 Aims

The aims of the Main Study were to:

- (a) determine whether both or only one of the two programs contributed to candidates' understanding of the light-dependent reaction of photosynthesis;
- (b) obtain evidence for the value, in terms of conceptual improvement of participants, of a multimedia program that incorporated many elements of Laurillard's Discourse Model and one that did not;
- (c) evaluate feedback that enhanced the development of knowledge and understanding;
- (d) generate guidance for potential users of learning software.

5.3 Revised data recording and test techniques

One of the potential problems, highlighted as a result of the Pilot was that the data recorded on-screen lacked visual clarity. Since these data were of potential use in the analysis of participant understanding, especially when using *Photosynthesis Explorer*, where participants were expected to type in descriptions of predictions, hypotheses and conclusions. In order to facilitate this a product known as Hypercam was used. Hypercam recorded all on-screen activity from the monitor, which supported text annotations, sound and screen notes.

As noted in the Pilot, the matched-pair test carried several advantages over the multiple-choice and two-tier multiple-choice tests, but its value as a device for measuring knowledge and understanding as a result of the use of either

program depended on the quality with which it was written. This quality depended not only on whether the task topics covered participant knowledge and understanding of the salient features of the light-dependent reaction, but also on maximising the chances that the tasks were completed from an understanding of the matched pairs comments rather than, for example, the presence or absence of single words – a legalistic approach. These potential problems of validity also applied to the pre-A level test in relation to misconceptions.

In order to answer these potential problems, assistance was sought from experts in the fields of test-setting and biology. These experts were from two Awarding Bodies, UCLES and EDEXCEL. In respect of the style of statements and response box, it was suggested that, in the case of style, the two statements should, as far as possible, be more parallel (of similar, though not of course identical, content) and of similar length thereby reducing the likelihood of a legalistic approach to answering the tasks by participants. However, in addition it was suggested that the response box required modification because ticking a choice alone and then offering an opportunity to comment was 'too tempting an option for some who wished to avoid writing'. The alternative strategy suggested was to use a confidence measurement to rate as a percentage of how confident they were to have selected an answer and then to invite them to give their reasons for their choice A or B.

Responses were not therefore tied to being right or wrong in the analysis but to the degrees of confidence ascribed to them. Support for this

approach comes from the work of Leclercq (1983), as well as earlier authors, such as de Finetti (1965) van Naerssen (1965) and Shuford et al. (1966).

More recent researchers too have discussed the validity of using confidence measures as a tool for defining students' knowledge. Gardner-Medwin & Gahan (2003) suggest that the use of such scores improve the reliability of multiple-choice tests and enable more precise discrimination between students. Bruce (2003) suggests there is a moderately positive correlation between achievements in English as a Foreign Language in Chinese students with the number of correct scores in a multiple-choice test for those obtaining the highest confidence measures. Fenna (2004) showed that after a teaching program the proportion of correct to incorrect responses with the highest confidence measure of 4 was 80% and progressively less to just over 20% with zero confidence.

Leclercq has quantified the confidence scale into six degrees of certainty, which he suggests represent the smallest unit of subtlety, usually represented in 20% intervals from 0 – 100%. LeClercq uses the term 'Degrees of Certainty' for these units and suggests also that values higher than 50% (60%, 80% and 100%) represent informed knowledge (metacognition) if a response is correct or, if wrong, dangerous knowledge. One recent study using a confidence value of more than 50% is reported by Crisp & Ward (in press) on the

Pedagogical Psychology Computer Assisted Assessment project. In the present study, these degrees of confidence are applied in two different ways, the first in which the whole confidence scale is used and the second in which only correct scores of 60% or higher, the so-called metacognitive values, are applied. This approach was used because it enabled the use of the whole spectrum of participants' numerical responses as well as their metacognitive scores, which are it is suggested representative of a sound level of understanding and enabled validation by correlation with written responses.

The content of the A-level test was revised to include all aspects of the light-dependent reaction of photosynthesis appropriate to A-level students and was inclusive of material in the A-level narrative (Figure 5.1). This was repeated for the pre-A level tasks so that they held material consistent with a pre-A level narrative (Figure 5.2) and with elicitation of misconceptions commonly held by students. The eight pre-A level tasks were on General Certificate of Education (GCSE) (Year 11) concepts of energy and photosynthesis, as well as factual recall on leaf structure. The first four of which were on basic concepts of energy and the last four on photosynthesis and leaf structure.

In summary, both sets of tasks (in the Task Booklet) were in the same format. In each task, participants were provided with an opening statement, which was either right or wrong. Each statement was followed by two alternative descriptions linked to the opening statement, only one of which was correct. Participants were then asked to respond by selecting one of the two alternative descriptions in relation to the opening statement. In addition, they

addition, they were asked both to rate their responses on a confidence scale of 0-100% in 20% intervals and to make a statement about the reasons for selecting one of the two alternatives.

Sixth form narrative on energy and photosynthesis

Students need to be aware of the following facts at A-level.

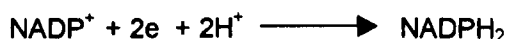
Light energy is trapped in the grana (in light harvesting units containing many pigments, including chlorophyll a) that are structures formed from special plasma membranes within chloroplasts. Each granum is made up of stacks of thylakoids, which are disc-like, having a fluid filled space within them, the lumen. Each disc contains many proton channels, which also hold a very special protein, which is an enzyme, variously named, but most commonly called ATP synthase.

In addition to containing chlorophyll and proton channels, the thylakoid membranes also possess electron carriers between two light harvesting units, the so-called Photosystems I and II.

Light energises electrons in the pigments of PS II so that these electrons are transferred from chlorophyll (a) (P 680) to an electron carrier, which is thereby reduced and the chlorophyll oxidised. This is a redox reaction. This reaction leaves an electron deficient chlorophyll (a) molecule, which must be filled by electron from somewhere. The source of electrons is water, which dissociates into electrons, protons and oxygen. The protons produced are held within the lumen of the thylakoid. This is known as the Hill reaction.

The electrons are transferred through a series of carriers between PS II and PS I and as they do so their excitation energy is reduced. The energy released is used to drive protons into the lumen causing a decrease in pH. This accumulation of protons opens proton channels in the membrane, so that they flow down the gradient created, activating the ATP synthase, enabling the production of ATP.

These two products, oxygen and ATP, are not the only ones produced as a result of the light-dependent phase. In terms of the energy demanded for its production, reduced NADP (or NADPH_2 or $\text{NADPH} + \text{H}^+$) does not have an equal in the whole of the light-dependent phase. Electrons reaching PS I are at a higher energy level than when they originally left water. In other words they have considerably more reducing power. When they are further energised by light, these electrons leave chlorophyll a (P 700) and sufficient energy is available to reduce NADP^+ to NADPH_2 , which becomes a powerful reducing agent.



Thus the products of the light-dependent reaction are ATP, NADPH_2 and O_2 . ATP and NADPH_2 are used in the production of glucose in the light-independent reaction being changed back to ADP and NADP^+ in the process.

Figure 5.1 A-level narrative on the light-dependent reaction of photosynthesis

Pre-A level narrative on energy and its relationship to photosynthesis

Students need to be aware that energy cannot be created or destroyed and that energy obtained by living organisms must be acquired, or transformed, from another source of energy. Energy is vital to life, since without it work cannot be done and no complex chemicals made. Some more obvious consequences, such as the absence of locomotion, muscle contraction or growth highlight the need for energy. In short, life cannot exist without it.

In living systems, the ultimate source of energy is sunlight, which is trapped by green plants, using the pigment chlorophyll. This pigment is held in special organelles called chloroplasts.

In these organelles, light energy is used to combine carbon dioxide and water to make carbohydrate (glucose) and oxygen. Moreover, the energy provided by light is somehow converted into chemical energy within organic chemicals, such as glucose, during the process of photosynthesis

Leaves are the main, though not the only, organs in which chloroplasts are found. Leaves are specially adapted to trap light efficiently and to provide the raw materials, carbon dioxide and water, which are transformed into carbohydrate and oxygen during photosynthesis.

Figure 5.2 Pre-A level knowledge expected of students studying the light-dependent reaction

Two examples of the final form of these tasks are shown below (Figures 5.3 and 5.4) and a whole set of tasks (within a task booklet) is to be found in Appendix B. Each task booklet was to be completed before each program's use, immediately afterwards and after some delay. The delayed post-test was an addition to the testing suite operated in the Pilot because it would provide additional evidence as to whether each program was effective or not.

<p>4. Light harvesting units containing chlorophyll and other pigments are held in membranes inside the chloroplast itself.</p>	
<p>A No</p> <p>A chloroplast is an organelle surrounded by a double membrane, which is called the chloroplast envelope. The use of the electron microscope reveals that there are raised dots on this envelope. This is evidence that the light harvesting units are on the outer membrane.</p>	<p>B Yes</p> <p>A chloroplast is an organelle surrounded by a double membrane. Using an electron microscope it is possible to observe raised dots on the inner membranes, but not on the surrounding double membrane itself. These raised dots are light harvesting units.</p>
<p>My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)</p> <p>On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.</p> <p>0% 20% 40% 60% 80% 100%</p> <p>Give reasons for your choice of A or B above</p>	

Figure 5.3 Example of an A-level task

<p>1. Energy can be transferred to different forms, such as electrical into light, and chemical into heat</p>	
<p>A Yes</p> <p>Currents of electricity travelling along wires can illuminate a light bulb, and coal will burn releasing heat.</p>	<p>B No</p> <p>All these different forms of energy exist in nature. Solar energy (sunlight) contains heat energy and consequently heats up the earth.</p>
<p>My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)</p> <p>On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.</p> <p>0% 20% 40% 60% 80% 100%</p> <p>Give reasons for your choice of A or B above</p>	

Figure 5.4 Example of a pre-A level task

5.4 Method

5.4.1 Participants

Forty students (called participants in the study) were used from Hereford Sixth Form College. They were in the first year (Year 12) of their A-level studies. All of them were biology students and thirty-eight had previously studied science at one of a number of eleven to sixteen schools in Hereford. The remaining two had attended Hereford Cathedral School. B grades or above were held by all participants, except one, who obtained C grades in Double Award Science, in GCSE, taken in Year 11, either in Double Award Science or in Biology. Of the twenty participants who used *Photosynthesis Explorer*, two obtained A*, seven A, ten B and one C in either Double Award Science or Biology; the grades for Open University's (Discovering Science) *Cells and Energy* users were six A*, four A and ten B, which suggested that this group was slightly better qualified. This was confirmed by their mean GCSE scores, which were 6.68 and 6.75 respectively.

All participants were familiar with ICT including the use of computers at school or college, since ICT was a compulsory part of the National Curriculum.

5.4.2 Materials

The materials required were a Panasonic video camera, hypercam software, audio tape recorder, computer and screen and the two items of photosynthesis software on photosynthesis, *Photosynthesis Explorer* and the *Cells and Energy* programs.

5.4.3 Procedure

In June 2003, The Head of Biology at Hereford Sixth Form College issued written requests, provided by the researcher, for participants to take part in the study. On each form they were given the opportunity to affirm their willingness to assist, to write down the name of the participant with whom they wished to work and the days and times at which they would be available. Participants were told that they would be taking part in an Open University study on the value of two pieces of software on learning about photosynthesis. They were also informed that there would be four parts to this, of which three would contain written tasks and one would involve working as pairs at the computer for approximately one hour.

Pre-test booklets were then issued and participants informed that the tasks inside were intended as tests of their knowledge before work commenced on the programs. It was emphasised that independent task responses were required and that source material was not to be employed. Finally, they were advised about the presentation of their answers in the response sections and urged to support their answers with prose in the spaces provided.

On the return of the booklets, they were marked and on the basis of the results, ten pairs were assigned to one program and ten to the other. However, it was not possible to retain an exact equivalence between groups on the basis of pre-test pre-A level scores, because pairs were re-assigned programs, because those selected were not always available for the lengthy periods required to complete the *Photosynthesis Explorer* program. After

checking scores, times when participants had indicated availability and further consultation with pairs, the participants' allotment to each program was modified. This meant that some, who could not be available for the two hours necessary, had to be assigned to the other program. As already stated, this resulted in a very slight academic bias towards those who employed the *Cells and Energy* program.

As each pair was introduced to the research room set up, data collection through audio- and video-tape commenced. As each pair prepared to use one of the programs, verbal instructions were issued. There was a general instruction that the objective was to find out about the light-dependent reaction. After that for *Cells and Energy*, pairs were told to go to 'Introduction to Photosynthesis' and then to follow the instructions on the program. For *Photosynthesis Explorer* a little more detail was initially required in order to become familiar with a route to travel. This entailed directing each pair to investigate three main menu sections in the following order: 'First Look', then 'Explorations' and finally 'Core Enquiries' and, in these last two, to use a limited number of sub-sections in a specified order (see Pilot, p. 134).

An observational schedule was used to provide additional notes regarding researcher activity or intervention and student activity (such as talk and working at the keyboard).

After completion of computer work, participants were issued with a new task booklet, which contained the same tasks as before. The tasks were completed in the research room. Two weeks afterwards, they were sent the

final task booklet, which once more contained the same tasks, and instructed to return it within one week. Only two participants failed to return a completed booklet and both of them had used the *Cells and Energy* program.

5.5 Findings from overall scores in tests

5.5.1 Introduction

The following section describes the overall findings from participant responses to test tasks on light, energy and photosynthesis set before and after the intervention of multimedia teaching programs on the topic of the light-dependent reaction of photosynthesis. The results are displayed in tabular and graphical form for both the pre-A level tasks of the test paper and those at A-level, followed by descriptions of the trends and patterns and finally by a statistical analysis.

No specific changes in participant response were expected to the pre-A level tasks as a result of using the multimedia programs. However, these data would provide not only information as to the consistency of participant response across the three test stages, but also evidence of changes in participant understanding at these more basic levels during the data gathering phase.

For the purposes of the analysis the staged tests are called the pre-tests, post-tests and delayed post-tests, whether at pre-A level or A-level. The pairs are identified by numbers 1 to 10 and members by letters A and B.

5.5.2 Procedure

Raw numerical responses were organised into:

- (A) Ordinal values, so that an incorrect response with 100% confidence scored 1, with 80% confidence 2, up to a score of 12 with a correct answer at 100% confidence. This had the advantage that it makes use of all the raw data presented by participants.
- (B) Cognitive (metacognitive) values, so that only those responses in which the participants were very confident in their correct answers (that is 60% or above) scored a single mark for each correct response. This had the advantage of providing scores that related to participants' secure conceptual knowledge and understanding.

Using the ordinal scoring system, in the pre-A level test tasks, this gave a possible total of 96 (8 tasks, with a total mark of 12 for each) and at A-level 180 (15 tasks) per participant. All the overall results are displayed in comparison to these possible maxima.

Using the cognitive rating system, the maxima are 8 (if all responses were credited with a value of >60%) for each pre-A level set of tasks and 15 for each set of A-level tasks per participant.

The results, analysis and discussion are developed below for the ordinal, and then the cognitive, data. This was done first through trends and patterns revealed by tables and graphs and then through statistical methods.

5.5.3 Pre-A level results

These results are displayed for ordinal data as outlined above and then for cognitive scores, first for overall scores and then for the first four tasks and then for the last four. The reasons for this are explained after the results for all tasks are displayed.

5.5.3.1 All pre-A level test tasks (ordinal data)

Overall mean scores ranged between 70.10 and 78.70, with the lowest individual score being 44.00 and the highest 95.00. These and the results for each test are recorded in Table 5.1 and Figure 5.5 below. The mean results for *Photosynthesis Explorer* ranged between 70.10 and 74.10 (with the range for individual scores being 44.00 to 93.00) and for *Cells and Energy* between 75.30 and 78.70 (with the range for individual scores being 52.00 to 95.00).

	Pre-A level scores (max. 96) <i>Photosynthesis Explorer</i>			Pre-A level scores (max 96) <i>Cells and Energy</i>		
	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 20	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 18
Mean	70.10	73.00	74.10	75.30	78.70	76.20
S.D.	10.20	11.86	10.33	9.30	12.17	11.62
Minimum	54.00	51.00	44.00	54.00	54.00	52.00
Maximum	91.00	93.00	87.00	93.00	94.00	95.00

Table 5.1 Summary of means and variability of scores in pre-A level tests (ordinal data)

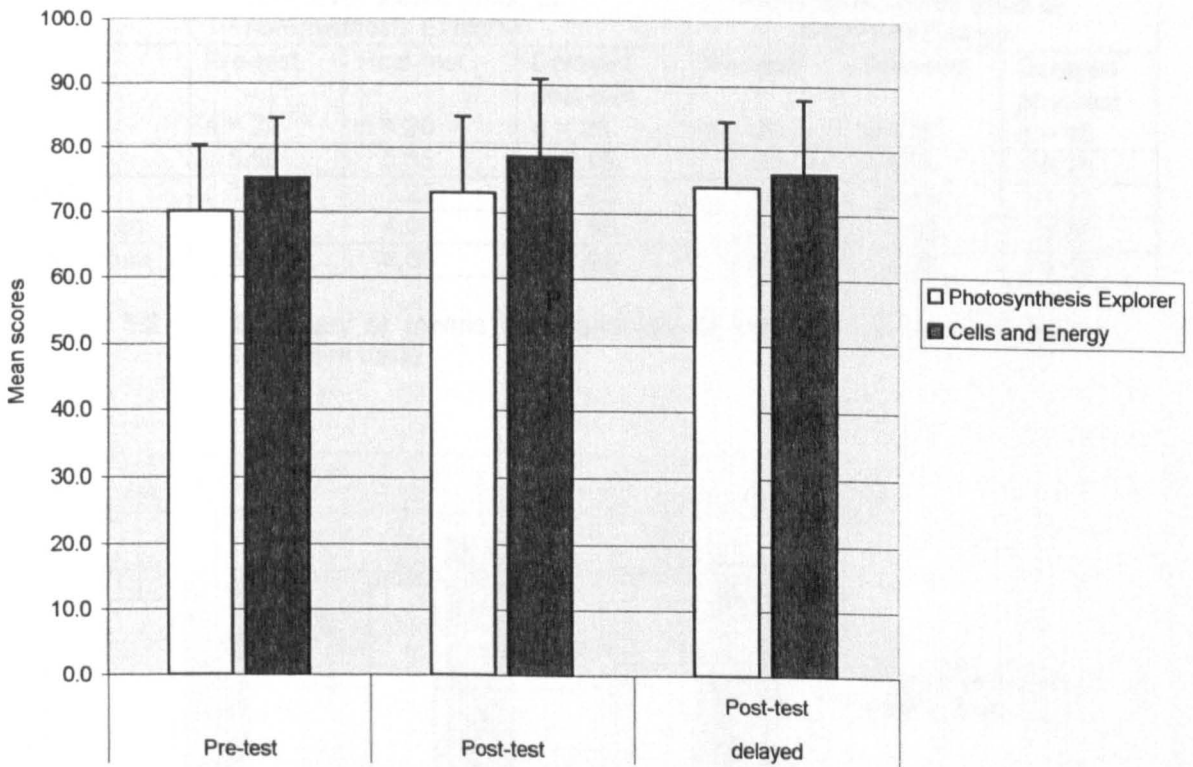


Figure 5.5 Bar chart of mean scores on pre-A level tests (ordinal data)

5.5.3.2 All pre-A level test tasks (cognitive data)

Overall mean scores ranged between 5.50 and 6.55, with the lowest individual score being 3.00 and the highest 8.00. These and the results for each test are recorded in Table 5.2 and Figure 5.6. The mean results for *Photosynthesis Explorer* ranged between 5.50 and 5.95 (with the range for individual scores being 3.00 to 8.00) and for *Cells and Energy* between 5.80 and 6.55 (with the range for individual scores being 3.00 to 8.00).

	Pre-A level scores (max. 8) <i>Photosynthesis Explorer</i>			Pre-A level scores (max 8) <i>Cells and Energy</i>		
	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 20	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 18
Mean	5.50	5.85	5.95	5.80	6.55	6.28
S.D.	1.24	1.23	1.05	1.40	1.15	1.23
Minimum	3.00	4.00	3.00	3.00	5.00	3.00
Maximum	8.00	8.00	7.00	8.00	8.00	8.00

Table 5.2 Summary of means and variability of scores in pre-A level tests (cognitive data)

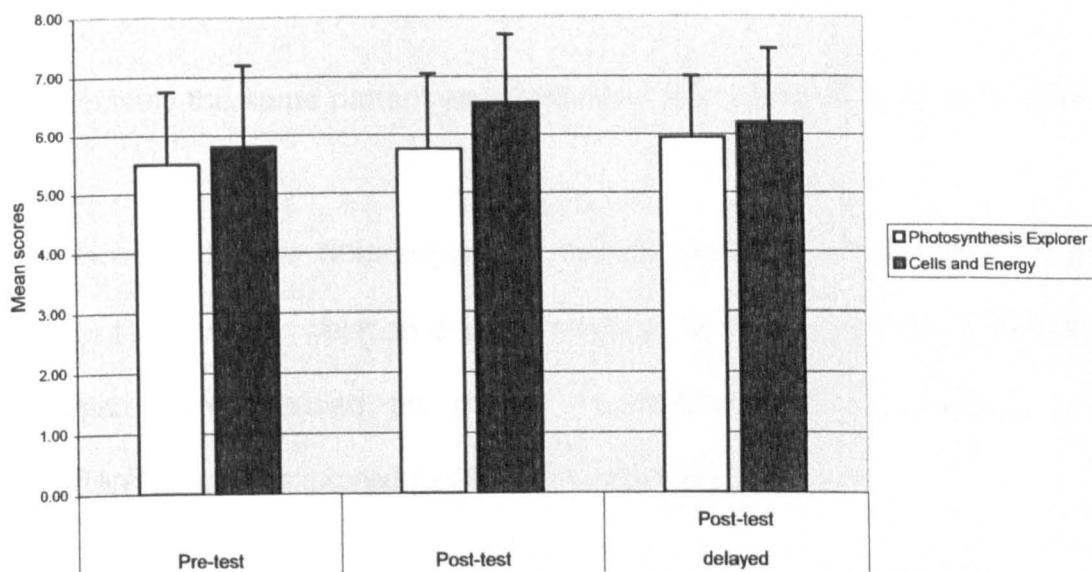


Figure 5.6 Bar chart of mean scores on pre-A level tests (cognitive data)

5.5.4 Analysis of overall Pre-A level test results

Participants who used the *Photosynthesis Explorer* program had a lower mean (on the ordinal scale out of a maximum of 96) compared with the *Cells and Energy* group at every stage of the testing process. Nevertheless the differences in mean scores were small and never greater than 5.20. The lowest mean of 70.10 represented 73% of the possible maximum and the highest mean of 78.70 represented 82%, which suggested a sound understanding of the basic concepts tested. There was a consistent improvement in scores amongst the three tests for Photosynthetic Explorer

users, whereas for *Cells and Energy* the scores peaked at the post-test stage, though the delayed post-test score was higher than the pre-test.

The higher score in the Pre-test suggested a higher level of knowledge and understanding by the users of the *Cells and Energy* program and was consistent with the other evidence obtained from their GCSE grades overall and specifically for those awarded for Biology or Double Award Science.

Precisely the same pattern emerged when the cognitive scale was used.

However, the raw data suggested that participants scored highly on the first four tasks, which were on energy concepts per se rather than on the last four, which were focused on energy in relation to photosynthesis. These differences are explored further in the next sub-section.

5.5.5 Results of two sub-divisions of pre-A level tests

5.5.5.1 Pre-A level test tasks 1-4 (ordinal data)

Overall mean scores ranged between 42.80 and 44.95, with the lowest individual score being 25.00 and the highest 48.00. These and the results for each test are recorded in Table 5.3 and Figure 5.7 below. The results for *Photosynthesis Explorer* ranged between 43.40 and 43.83 (with the range for individual scores being 26.00 to 48.00) and for *Cells and Energy* between 42.80 and 44.95 (with the range for individual scores being 25.00 to 48.00).

	Pre-A level scores, tasks 1-4 (max. 48) <i>Photosynthesis Explorer</i>			Pre-A level scores, tasks 1-4 (max.48) <i>Cells and Energy</i>		
	Pre-test	Post-test	Delayed post-test	Pre-test	Post-test	Delayed post-test
	n = 20	n = 20	n = 20	n = 20	n = 20	n = 18
Mean	43.60	43.40	43.83	42.80	44.95	43.72
S.D.	4.58	6.95	4.94	5.69	3.44	5.14
Minimum	35.00	26.00	35.00	25.00	36.00	34.00
Maximum	48.00	48.00	48.00	48.00	48.00	48.00

Table 5.3 Summary of means and variability of scores on first four tasks of each of three pre-A level tests (ordinal data)

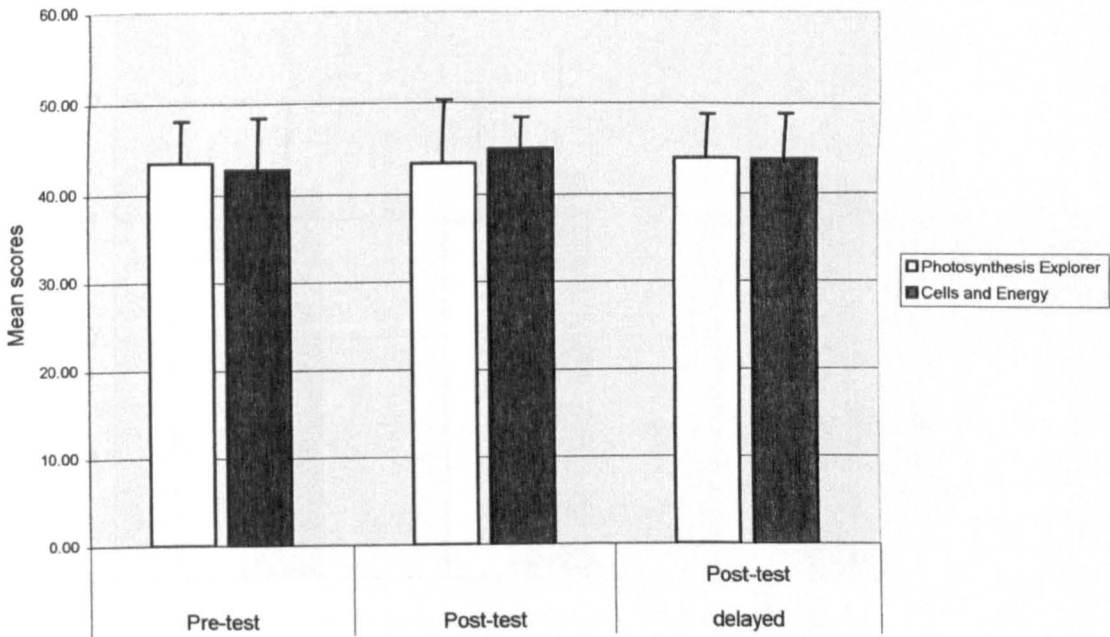


Figure 5.7 Bar chart of mean scores (max.48) on first four tasks on each of three pre-A level tests (ordinal data)

5.5.5.2 Pre-A level test tasks 5-8 (ordinal data)

Overall mean scores ranged between 26.50 and 32.50, with the lowest individual score being 9.00 and the highest 48.00. These and the results for each test are recorded in Table 5.4 and Figure 5.8 below. The results for *Photosynthesis Explorer* ranged between 26.50 and 29.80 (with the range for individual scores being 9.00 to 47.00) and for *Cells and Energy* between 32.50 and 33.70 (with the range for individual scores being 10.00 to 48.00).

	Pre-A level scores, tasks 5-8 (max. 48) <i>Photosynthesis Explorer</i>			Pre-A level scores, tasks 5-8 (max.48) <i>Cells and Energy</i>		
	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 20	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 18
Mean	26.50	29.60	29.80	32.50	33.70	32.50
S.D.	9.34	9.58	9.16	7.29	10.82	10.05
Minimum	11	11	9	19	10	16
Maximum	46	45	47	46	48	47

Table 5.4 Summary of means and variability of scores on last four tasks of each of three pre-A level tests (ordinal data)

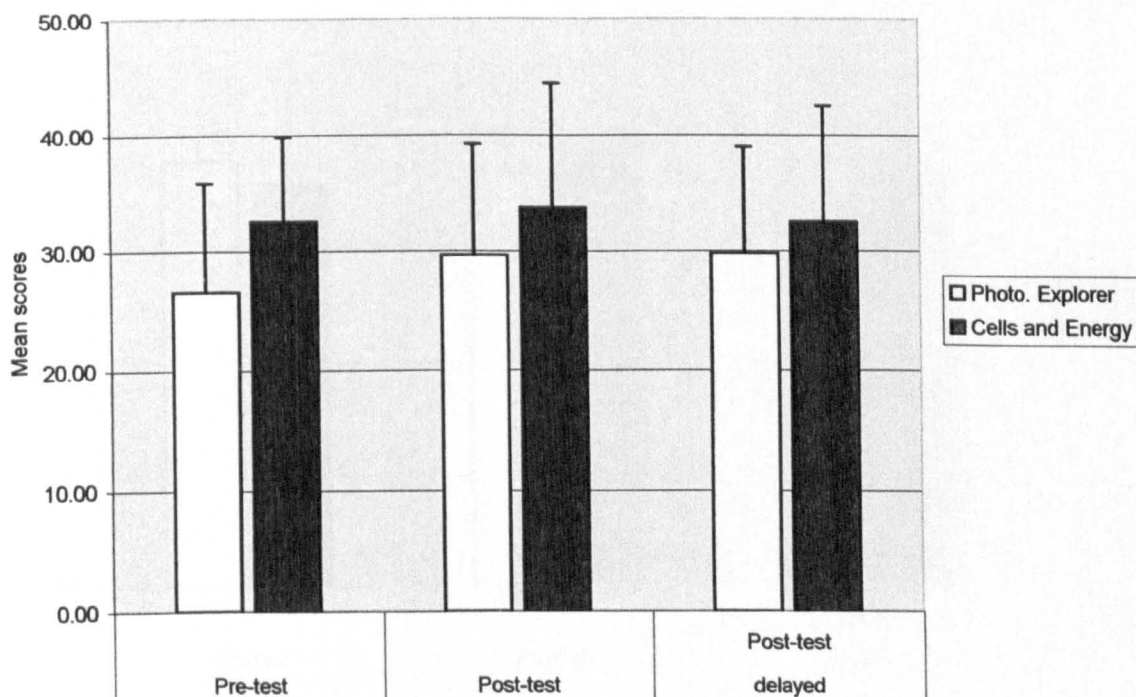


Figure 5.8 Bar chart of mean scores (max.48) on last four tasks on each of three pre-A level tests (ordinal data)

5.5.5.3 Pre-A level test tasks 1-4 (cognitive data)

Overall mean scores ranged between 3.55 and 3.90, with the lowest individual score being 2.00 and the highest 4.00. These and the results for each test are recorded in Table 5.5 and Figure 5.9 below. The results for *Photosynthesis Explorer* ranged between 3.65 and 3.75 (with the range for individual scores being 2.00 to 4.00) and for *Cells and Energy* between 3.55 and 3.90 (with the range for individual scores being 1.00 to 4.00).

	Pre-A level scores, tasks 1-4 (max. 4) <i>Photosynthesis Explorer</i>			Pre-A level scores, tasks 1-4 (max.4) <i>Cells and Energy</i>		
	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 20	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 18
Mean	3.75	3.65	3.75	3.55	3.90	3.72
S.D.	0.55	0.67	0.44	0.89	0.31	0.46
Minimum	2.00	2.00	3.00	1.00	3.00	3.00
Maximum	4.00	4.00	4.00	4.00	4.00	4.00

Table 5.5 Summary of means and variability of scores on first four tasks of each of three pre-A level tests (cognitive data)

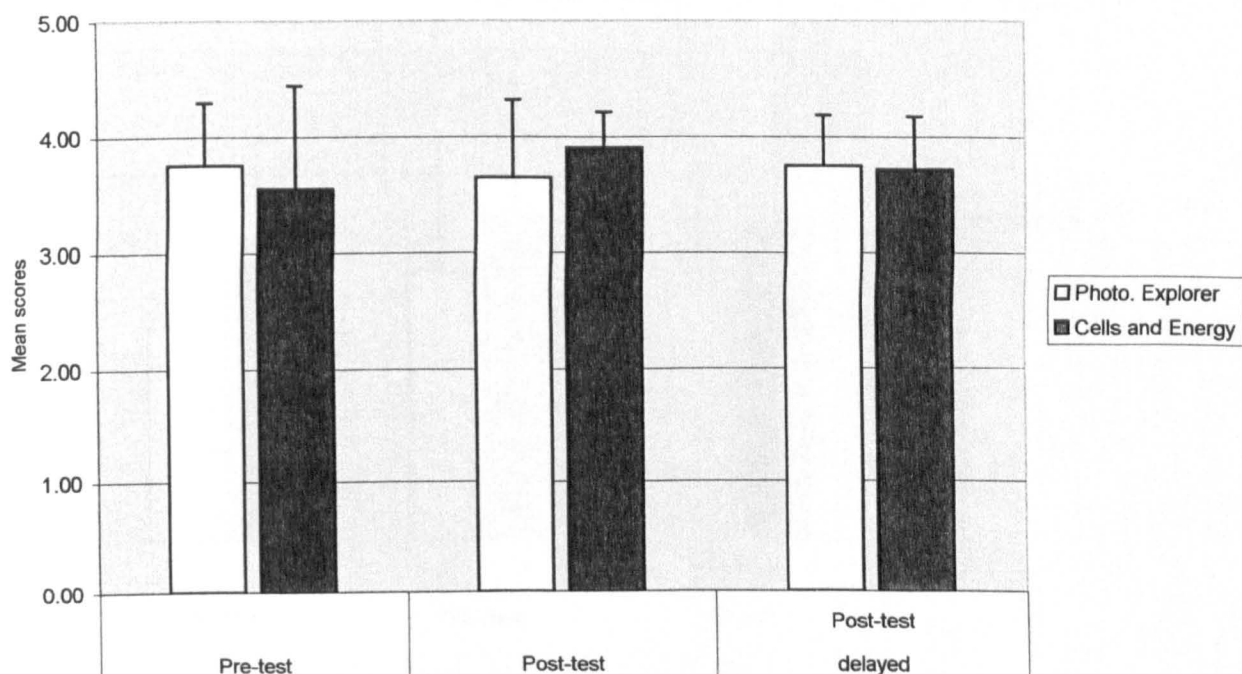


Figure 5.9 Bar chart of mean scores (max.4) on first four tasks on each of three pre-A level tests (cognitive data)

5.5.5.4 Pre-A level test tasks 5.8 (cognitive data)

Overall mean scores ranged between 1.75 and 2.65, with the lowest individual score being 0.00 and the highest 4.00. These and the results for each test are recorded in Table 5.6 and Figure 5.11 below. The results for *Photosynthesis Explorer* ranged between 1.75 and 2.20 (with the range for individual scores being 2.00 to 4.00) and for *Cells and Energy* between 2.25 and 2.65 (with the range for individual scores being 0.00 to 4.00).

	Pre-A level scores, tasks 5-8 (max. 4) <i>Photosynthesis Explorer</i>			Pre-A level scores, tasks 5-8 (max.4) <i>Cells and Energy</i>		
	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 20	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 18
Mean	1.75	2.20	2.20	2.25	2.65	2.58
S.D.	1.07	1.06	1.01	1.02	1.09	1.10
Minimum	0	1	0	0	1	1
Maximum	4	4	4	4	4	4

Table 5.6 Summary of means and variability of scores on last four tasks on each of three pre-A level tests (cognitive data)

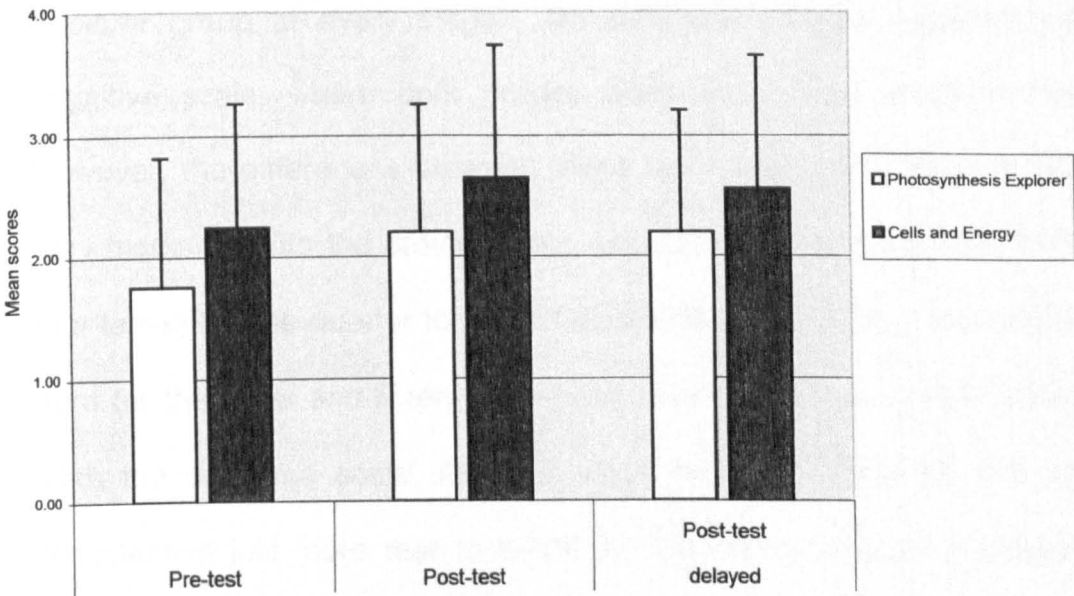


Figure 5.10 Bar chart of mean scores (max.4) on last four tasks on each of three pre-A level tests (cognitive data)

5.5.6 Analysis of sub-divided pre-A level test results

Whichever scale was used, participants scored more highly on the first four tasks than on the last four. There was very little difference either between the performances of the participants across the three tests for the first four tasks or between the users of one program or the other. Answers were nearly always correct for *Photosynthesis Explorer* users. Out of the total of 240 responses - only 15 were incorrect and on the cognitive score only 2 correct responses fell below the cognitive threshold of 60%. For *Cells and Energy*

program users a very similar picture emerged. Answers once more were nearly always correct and out of 232 responses in total only 8 were incorrect and on the cognitive score only 7 correct responses fell below the cognitive threshold of 60%.

For the last four tasks a quite different pattern emerged. When the ordinal scale was applied, *Cells and Energy* users outperformed the *Photosynthesis Explorer* group at every stage. No such pattern was apparent with the cognitive scale, where both groups were much more similarly matched. However, the differences between these test results, and the first four were very marked. With the ordinal scale, scores fell (when compared to the first four tasks) by one-quarter for the *Photosynthesis Explorer* group and by one-third for the *Cells and Energy* group and consistently so across three tests. With the cognitive scale, the falls were even more marked with up to a reduction of just more than one-half for the *Photosynthesis Explorer* group and just more than one-third for *Cells and Energy* group. Nevertheless these reductions were most marked at the pre-test stage and consistent thereafter suggesting that the programs were influencing participants' understanding of the concepts tested in these last four tasks.

Certain participants appeared to hold strong misconceptions on most of the topics tested here, as judged by their raw ordinal scores, throughout the testing period. For example, scores of 9, 10 and 11 (see Table 5.4) did suggest high confidence in most if not all the wrong answers and even a score of 19 suggested some strong misconceptions (since the vast majority of

participants held >60% confidence values either way). These data suggested that Participants 2B, 5A (P3)* and 6A (P5) from the *Photosynthesis Explorer* group and Participants 9B, 10A and 10B from the *Cells and Energy* group held misconceived ideas. Others possessed a sound understanding, namely Participants 1A, 7B (P2), 8A and 9B from the *Photosynthesis Explorer* group and Participants 1A, 1B, 5A (C9), 5B (C10), 6A, 6B and 7B from the *Cells and Energy* group. One participant, 5A (P3), from the *Photosynthesis Explorer* group was a distinct outlier with only 4 of the 12 answers correct (over the three tests), of which only 1 was awarded a high cognitive score.

5.5.7 Results of A-level tests

5.5.7.1 Introduction

The overall results from the participant responses to these tasks are shown, as before, as comparative tables and bar graphs to show the overall changes in the mean scores in each of the tests in each program, first for the ordinal, and then for the cognitive, data.

5.5.7.2 A-level tests (ordinal scale)

Overall mean scores ranged between 101.90 and 130.40, with the lowest individual score being 77.00 and the highest 167.00. These and the results for each test are recorded in Table 5.7 and Figure 5.11 below. The mean results for *Photosynthesis Explorer* ranged between 101.90 and 130.40 (with the range for individual scores being 83.00 to 157.00) and for *Cells and Energy* between 103.40 and 124.45 (with the range for individual scores being 77.00 to 167.00).

*Identification of members in Chapters 7 and 8

	A-level scores (max. 180) <i>Photosynthesis Explorer</i>			A-level scores (max 180) <i>Cells and Energy</i>		
	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 20	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 18
Mean	101.90	130.40	119.75	103.40	124.45	119.22
S.D.	13.52	18.68	16.11	14.26	16.98	20.68
Minimum	83.00	89.00	94.00	77.00	102.00	87.00
Maximum	130.00	157.00	150.00	130.00	167.00	153.00

Table 5.7 Summary of means and variability of scores in A-level tests (ordinal data)

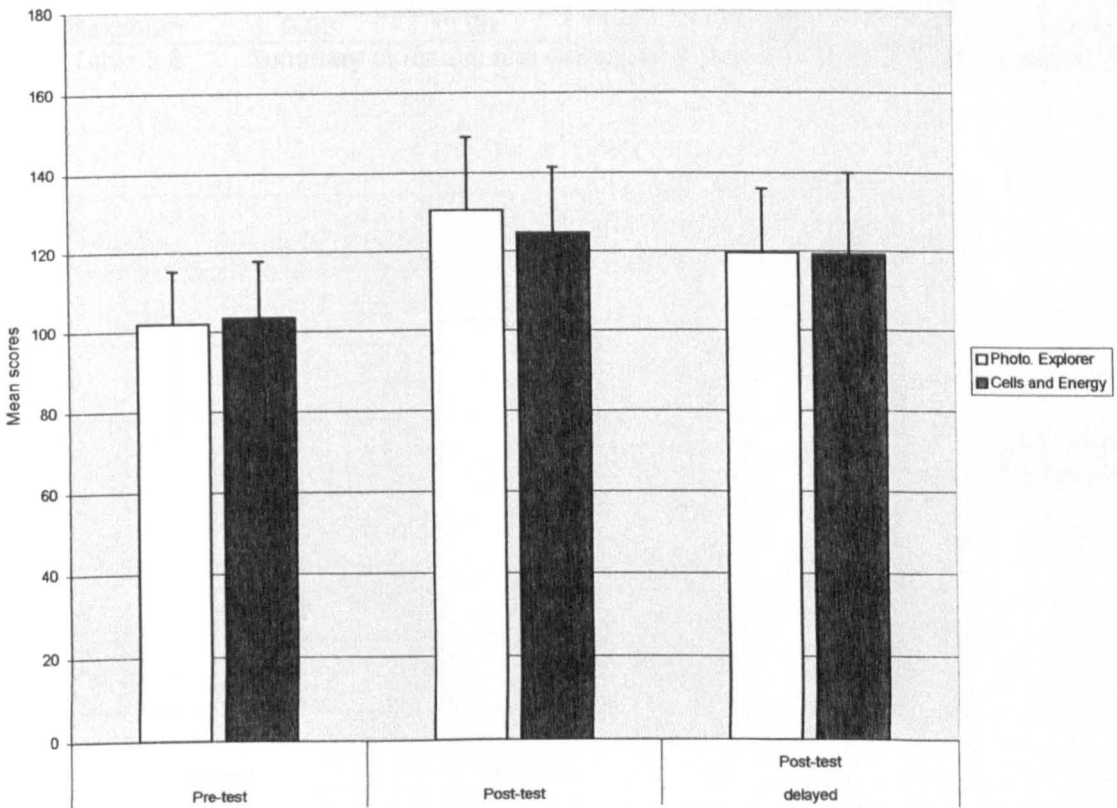


Figure 5.11 Bar chart of mean scores (max. 180) in A-level tests (ordinal data)

5.5.7.3 A-level tests (cognitive scale)

Overall mean scores ranged between 3.30 and 9.45, with the lowest individual score being 0.00 and the highest 13.00. These and the results for each test are recorded in Table 5.8 and Figure 5.12 below. The mean results for *Photosynthesis Explorer* ranged between 3.30 and 9.45 (with the range for

individual scores being 0.00 to 13.00) and for *Cells and Energy* between 3.65 and 8.25 (with the range for individual scores being 0.00 to 13.00).

	A-level scores (max. 15) <i>Photosynthesis Explorer</i>			A-level scores (max 15) <i>Cells and Energy</i>		
	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 20	Pre-test n = 20	Post-test n = 20	Delayed post-test n = 18
Mean	3.30	9.45	7.20	3.65	8.25	7.00
S.D.	2.64	2.70	2.95	3.73	2.32	3.77
Minimum	0.00	4.00	2.00	0.00	5.00	1.00
Maximum	9.00	13.00	11.00	11.00	13.00	13.00

Table 5.8 Summary of means and variability of scores in A-level tests (cognitive data)

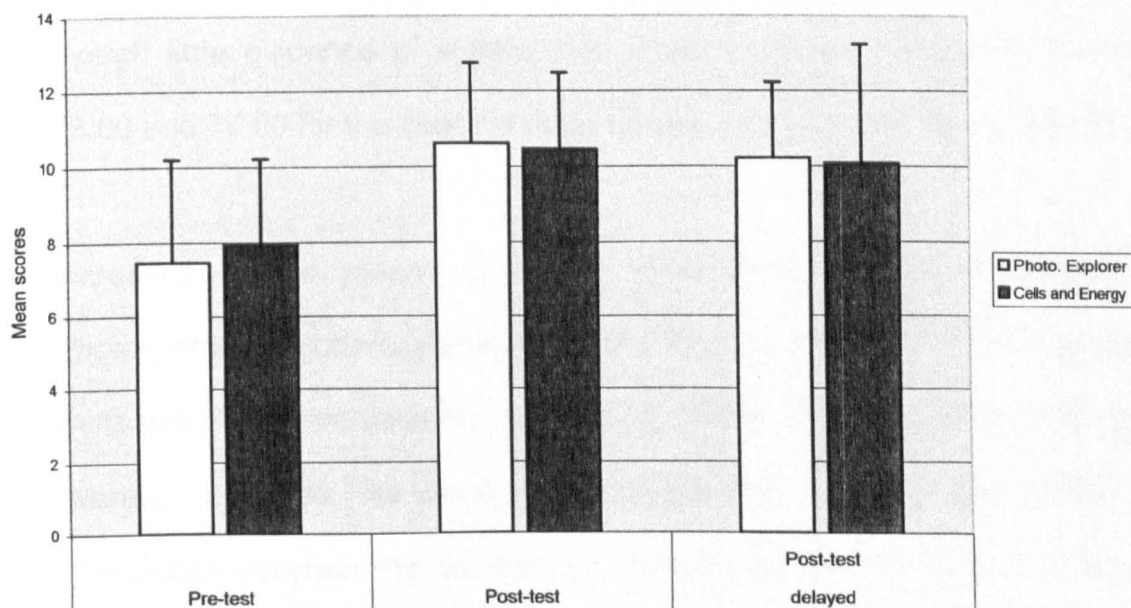


Figure 5.12 Bar chart of mean scores (max. 15) in A-level tests (cognitive data)

5.5.8 Analysis of A-level test results

Both programs showed an increase in the mean score at the post-test stage, and a reduction in the delayed post-test, whichever scoring system was used, though the mean score at this last stage remained higher than in the pre-test.

Before the results were analysed in detail it was important to put those where the ordinal scale was used into context. A participant who delivered incorrect answers to all fifteen tasks, with a 0% confidence rating, would achieve a mean score of 90.00 (15 x 6). Therefore the mean scores in the pre-tests of 101.90 and 103.40 could suggest that almost all participants had achieved correct answers to every task, but with zero confidence in any of them (mean score of 105). In reality, there was considerable variation in the responses to the pre-test tasks, as was shown by the standard deviations of 13.52 and 14.26 for *Photosynthesis Explorer* and *Cells and Energy* users respectively, though little evidence of widely held misconceptions. Minimum values of 83.00 and 77.00 for the users of these programs supported this contention.

Increases in the mean scores, by 28% (from 101.90 to 130.40) for *Photosynthesis Explorer* participants and by 20% (from 103.40 to 124.45) for *Cells and Energy* participants, suggested modest improvements in confidence overall. Even so, the large standard deviations (18.68 and 16.98) and differences between the lowest and highest scores (89.00 to 157.00 and 102.00 to 167.00) demonstrated the non-uniformity of these improvements. In other words, these results suggested that participants had achieved high confidence scores in some/more tasks as a result of the use of these programs. In addition, higher minimum and maximum scores were recorded for those who used the *Cells and Energy* program than for *Photosynthesis* although overall, comparatively modest gains were achieved. At the delayed-post-test stage, the decline in the overall score was more marked for *Photosynthesis Explorer* participants, though both groups realised a similar

mean score of 119.75 (*Photosynthesis Explorer Group*) and 119.22 (*Cells and Energy*).

Whilst these trends and patterns illustrated the overall changes in scores and the confidence participants placed in their responses, they failed to demonstrate the overall number of correct responses to the tasks at each stage and more important, perhaps, the number of these at or above the cognition level of 60%. These changes are explored below using the mean cognitive scores.

Scores showed a pattern that was similar, though more distinct, than that demonstrated when the ordinal score was employed. Mean scores more than doubled from pre-test to post-test (from 3.30 to 9.45 for *Photosynthesis Explorer* and from 3.65 to 8.25 for *Cells and Energy*) and then fell back in the delayed post-test, though with mean scores that were either almost double (*Cells and Energy*) or more than double those at the pre-test stage. There was nevertheless considerable variation in the scores as demonstrated by the high standard deviations (between 2.32 and 3.77) and the high range of scores. Scores ranged by as much as 11 marks (0 to 11) at the pre-test stage and by 9 marks (4 to 13) in the post-test. Whilst these differences demonstrated a wide range of response, it was possible that certain participants were demonstrating cognitive change and that a number of them maintained it at the delayed-post-test stage, where the range was 12 marks (1 to 13). This is developed in Chapter 7.

5.6 Discussion of findings

The pre-A level task results suggested that overall participants held a sound understanding of the concepts investigated in the first four tasks, which were either about energy in general (the first two) or general energy tasks in relation to living organisms. The levels of understanding were unchanged throughout the investigation. The other four tasks revealed very mixed results at the pre-test stage, suggesting that at least some participants held misconceived ideas either about light energy and photosynthesis or about chloroplasts and their distribution in plants. Responses to all of these tasks were affected by the use of the program. Whether or not the knowledge and understanding revealed in the pre-A level test affected participants' ability to learn about the light-dependent reaction of photosynthesis is explored in a statistics sub-section (5.7.5).

The A-level data suggested that both programs affect participants' understanding of the light-dependent reaction both short- and long-term. In fact, participants in general show improved knowledge and understanding. When the cognitive score was applied high improvements were suggested, especially at the post-test stage, but also long-term. Whether or not these changes are statistically significant is explored in the next section (Section 5.7).

5.7 Statistical analysis

5.7.1 Introduction

From the statistical point of view, the research had a mixed design, with one between subjects factor (the programs) and one within subjects factor (the tests). In order to test the effects of each on the outcomes, SPSS packages were employed. A Repeated Measures program (General Linear Model), which is essentially a two factor analysis of variance, was used to test the statistical significance of the within and between subject factors both as a whole and for each pair of tests. Second, another variable for which data were available, the pre-A level test results, were introduced as co-variates in order to determine whether the differences in performance here would affect the statistical significance of the A-level test results. Finally, a correlation statistic (Pearson Correlation) was used to test if there was a statistically significant correlation between the pre-test scores and those of the pre-A level test.

5.7.2 Background to the tests

Whilst the various graphs illustrate the overall performance of the participants on each of the tests for each of the programs, it was important to discover whether the differences previously described occurred purely by chance or whether there was a strong likelihood that they would occur again. This was determined by undertaking a two-factor analysis of variance, followed by pair wise (multiple) comparisons of the within and between subject factors. The calculated values were then compared to critical values at $P < 0.05$, $P < 0.01$, $P < 0.005$, $P < 0.001$ and $P < 0.0005$. If the calculated value was greater than the critical value at any of these probability levels, then the differences were

statistically significant. A $P < 0.05$ indicates a significant difference and $P < 0.0005$ indicates a very highly significant difference.

5.7.3 Results for A-level test scores

First, the raw data were converted into an interval (1-12) scale, since this used all the data available, as previously described and, secondly, into a cognitive score (maximum 15 for each participant) for those participants with each correct answer at a confidence level of 60% or more yielding a single score for each of the fifteen tasks. The totals for each participant for each test and for each program were then calculated. The results of these tests are described below.

5.7.3.1 Results for ordinal scores

The repeat measures analysis demonstrated that there was a very highly significant difference ($P < 0.0005$) in the scores on the tests. When the changes between the scores for any pairs of tests for each of the two programs were compared, there were very highly significant differences between the pre- and post -test scores as well as between those of the pre- and delayed post-test ($P < 0.0005$), whilst there was a significant difference ($P < 0.05$) between the post and delayed post-test measures.

The analysis also showed that there were no statistically significant differences between the other main effect, that is the program, at any stage. In addition, there was no interaction either. These tests suggest that there was no difference in the overall effect of the two programs on the participants' knowledge and understanding of photosynthesis. The results are tabulated below in Tables 5.9 and 5.10.

Source of variation	d.f.	F value	P
Within subject factors (the tests)	2	42.818	< 0.0005
Interaction (tests and programs)	2	1.271	0.287
Between subject factors (the programs)	1	0.275	0.603

Table 5.9 Repeat measures A-level test analysis (General Linear Model) from SPSS (ordinal data)

Source of variation		d.f.	F value	P
Within-subjects factors (tests)	Pre to Post	1	84.174	< 0.0005
	Interaction	1	1.903	0.176
Between subjects factors (programs)	<i>Photosynthesis Explorer / Cells and Energy</i>	1	0.271	0.606
Within-subjects factors (tests)	Pre to Delayed - post	1	45.061	< 0.0005
	Interaction	1	0.082	0.776
Between subjects factors (programs)	<i>Photosynthesis Explorer / Cells and Energy</i>	1	0.002	0.965
Within subjects factors (tests)	Post to Delayed-post	1	6.743	< 0.05
	Interaction.	1	1.389	0.246
Between subjects factors (programs)	<i>Photosynthesis Explorer / Cells and Energy</i>	1	0.609	0.440

Table 5.10 General linear model A-level test analysis (multiple comparison) (post hoc) (ordinal data)

5.7.3.2 Results for cognitive scores (correct response at 60%+ confidence)

The repeat measures analysis demonstrated that there was a very highly significant difference ($P < 0.0005$) in the scores on the A-level test tasks.

However, there was no significant effect of the programs. When the changes between the scores for any pairs of tests for each of the two programs were compared, there were very highly significant differences between the pre- and post test scores as well as between those of the pre- and delayed post test and post and delayed post test ($P < 0.0005$).

The analysis also showed that there was no statistically significant difference between the programs, at any stage. In addition, there was no statistically significant interaction. However, there was a suggestion that there was some interactive effect between the program used and the test result differences between the pre- and post-test stages ($P = 0.051$). In other words, the differences between the scores on the pre- and post-tests were in part possibly dependent on the program used. *Photosynthesis Explorer* users showed a higher post-test gain than *Cells and Energy* users. Nevertheless, this interactive effect was not significant in the initial, overall analysis ($P = 0.202$). The full results are tabulated in Tables 5.11 and 5.12.

Source of variation	d.f.	F value	P
Within subject factors (the tests)	2	91.057	< 0.0005
Interaction (tests and programs)	2	1.635	0.202
Between subject factors (the programs)	1	0.271	0.606

Table 5.11 Repeat measures analysis of A-level results (General Linear Model) from SPSS (cognitive score)

Source of variation		d.f.	F value	P
Within-subjects factors (tests)	Pre to Post	1	194.869	< 0.0005
	Interaction	1	4.051	0.051
Between subjects factors (programs)	<i>Photosynthesis Explorer / Cells and Energy</i>	1	0.261	0.613
Within-subjects factors (tests)	Pre to D.P.	1	92.818	< 0.0005
	Interaction	1	0.198	0.659
Between subjects factors (programs)	<i>Photosynthesis Explorer / Cells and Energy</i>	1	0.001	0.978
Within subjects factors (tests)	Post to D.P.	1	14.842	< 0.0005
	Interaction.	1	1.492	0.230
Between subjects factors (programs)	<i>Photosynthesis Explorer / Cells and Energy</i>	1	0.774	0.385

Table 5.12 General linear model A-level test analysis (multiple comparison) (post hoc) (cognitive score)

5.7.4 Conclusions

Using the ordinal scale, the statistical analysis suggested that both programs were effectively bringing about improvements in participants' knowledge and understanding of photosynthesis, though the overall results did not depend on the program used. The improvements were both short-term and long-term, since overall the changes in score were highly significant between pre- and post responses, and between pre- and delayed post- ones. Nevertheless there was also a significant reduction in knowledge and understanding from the post- to delayed post-tests.

The conclusions were essentially the same when the cognitive scores were employed. Both programs were effective in producing highly significant improvements in knowledge and understanding both long- and short-term. Overall, these effects did not depend on the program used, though there was a weak possibility that one of the programs (*Photosynthesis Explorer*) added somewhat more cognitive gain than the other. Nevertheless, even though there were significant gains long-term, the reduction in knowledge and understanding two-three weeks after the programs were used was also highly significant, suggesting the possibility that participants were no longer so confident in their responses to some of the tasks as they were immediately after the use of the programs.

5.7.5 Results for A-level test scores using the pre-A level test scores as co-variables

Whilst the pre-A level pre-test was used to determine evidence of misconceptions at the outset and to look for possibilities of their effects on learning about the light-dependent reaction (see Section 5.3), the fact that participants re-took this test (along with the A-level test in the Task Booklet), left open the possibility that the changed scores in A-level tests were being influenced by the changed knowledge and understanding demonstrated by the pre-A level tests. Therefore the following analyses were undertaken that used within subject factors – the A-level tests and between subject factors – the pre-A level tests, for both the ordinal and cognitive data.

5.7.5.1 Using the ordinal scale

The results showed that there was no significant difference in the A-level test results, no interaction between the A-level test scores and pre-A level ones, as well as between the A-level test results and, finally, no significant difference (of the test results) between the programs used (Table 5.13).

Source of variation		df	F value	P
Within-subjects factors	(A-level tests)	2	1.433	0.246
Interaction	(A-level tests and covariate pre-A level test (1) pre-test	2	1.687	0.193
	(A-level tests and covariate pre-A level test (2) post-test	2	0.406	0.668
	(A-level tests and covariate pre-A level test (3) d- post-test	2	0.009	0.991
	(tests and program)	2	1.402	0.253
Between-subjects factors	Pre-A level test (1) pre-test	1	0.913	0.346
	Pre-A level test (2) post-test	1	0.055	0.816
	Pre-A level test (3) d-post-test	1	0.663	0.421
	Program	1	1.028	0.318

Table 5.13 Repeat measures analysis of A-level test results (General Linear Model) from SPSS (ordinal data) including covariates

5.7.5.2 Using the cognitive scale

The results (Table 5.14) suggested that there was a highly significant difference in the A-level test results, no interaction between the A-level test scores and pre-A level ones, as well as between the A-level test results and, finally, no significant difference (of the test results) between the programs used.

Source of variation		df	F value	P
Within-subjects effects	(A-level tests)	2	5.913	0.004 < 0.005
Interaction	A-level tests and covariate pre-A level test (1) pre-test	2	2.598	0.082
	A-level tests and covariate pre-A level test (2) post-test	2	2.187	0.120
	A-level tests and covariate pre-A level test (3) d-post-test	2	0.161	0.852
	(tests and program)	2	1.495	0.232
Between-subjects effects	Pre-A level test (1) pre-test	1	0.455	0.505
	Pre-A level test (2) post-test	1	0.165	0.687
	Pre-A level test (3) d-post-test	1	1.906	0.177
	Program	1	9.593	0.490

Table 5.14. Repeat measures analysis of A-level test results (General Linear Model) from SPSS (cognitive data) including covariates

5.7.6 Discussion of A-level results with co-variables

The 'no significant' effect of the tests using ordinal data was a surprising result, but the background variability in the pre-A level scores was probably not invalidating the highly significant difference between the A-level scores when the ANOVA test was applied without them. Three reasons are suggested for this:

- (A) The pre-A level scores as an entire entity did not represent background variability irrespective of the multimedia programs.
- (B) It was probably not the pre-A level scores that might be affecting those at A-level in the post- and delayed post-tests. It was possible

that prior to undertaking the post-test pre-A level section of the Task Booklet, for example, participant knowledge and understanding had changed and indeed improved, since completing the pre-test tasks. This was possible, though much more likely was the possibility that the multimedia programs were affecting participants' responses to these tasks rather than their knowledge about these pre-A level topics influencing their responses to the A-level set. As was explained in the graphical section, the last four tasks of the pre-A level set, which were on the topic of photosynthesis, accounted for almost all the variability shown in the pre-A level tests. The more general topics (the first four tasks) were very consistently answered throughout.

(C) There were no significant statistical differences between the pre-A level test scores or between the programs used, as is shown in the first table (Table 5.15) below.

Source of variation	d.f.	F value	P
Within subject factors (the tests)	2	1.435	0.245
Interaction (tests and programs)	2	0.544	0.583
Between subject factors (the programs)	1	2.152	0.153

Table 5.15 Repeat measures analysis of pre-A level test results (General Linear Model) from SPSS (ordinal data)

With the cognitive data, whilst the result remains statistically significant, the introduction of the pre-A level test scores reduces the confidence that the programs are indeed producing the differences described in the graphical analysis.

Even so, and for the reasons, previously explained, the use of the co-variable may not have validity in changing the very highly significant differences found without them. However, the significant P value for the pre-A level data (See Table 5.16) is a cause both for caution and for explanation. It was possible, that the gains being made in the pre-A level scores from pre-test to delayed post-test are possibly influencing the outcome in the A-level tests and therefore reduce the effectiveness of the programs' efficacy in promoting change. However, it is not the changed scores in the pre-A level tests that are promoting the change, but rather the program that is affecting the pre-A level test scores as previously explained.

Source of variation	d.f.	F value	P
Within subject factors (the tests)	2	3.523	0.035 <0.05
Interaction (tests and programs)	2	0.963	0.386
Between subject factors (the programs)	1	1.838	0.184

Table 5.16 Repeat measures analysis of pre-A level test results (General Linear Model) from SPSS (cognitive score)

5.7.7 Correlation statistics

Finally, a further source of evidence about the influence of the pre-A level test scores was sought. If, as was shown, in the graphical analysis section participants involved with *Cells and Energy* program gained a higher mean score on the pre-A level pre-test than those involved with *Photosynthesis Explorer*, then this might influence the A-level pre-test score, since not only might they obtain higher scores, but also be capable of greater gains because of their firm foundation knowledge. If a significant correlation was found between the participants' individual scores in the pre-A level and A-level test,

then participants who used one program might be expected to perform differently, since the means for both pre-A level pre-tests were not the same. As is illustrated below (Table 5.17), there were no statistically significant correlations when either the ordinal or cognitive measures were used.

There was no statistically significant correlation between the pre-A level pre-test scores and the A-level pre-test ones, as is shown in the final table below. This suggests that the A-level test score (pre-test) is independent of the pre-A level one and when this test was repeated for the pre-A level pre-test scores against the A-level post-test scores, non-significant results were again obtained.

	Pearson correlation significance values
Scores pre-test pre-A level and pre-test A-level (ordinal data)	0.121
Scores pre-test pre-A level and pre-test level (cognitive data)	0.230

Table 5.17 Pearson correlation significance values between pre-test pre-A level scores and pre-test A-level scores

5.7.8 Overall conclusions

A large number of statistical possibilities were explored in order to determine the statistical significance of the data. As concluded earlier, the significance values, when A-level scores alone were used, supported the view that the programs were promoting development of knowledge and understanding of the light-dependent reaction. However, whilst the programs were promoting change, the overall effect of the two programs was similar, so that there was no significant difference between the test scores when the effects of the programs were compared.

When a co-variate, the pre-A level scores were introduced the significance of the differences was called into question, at least so far as the ordinal score was concerned. However, as explained, this variability is probably not a factor in learning the topic, but rather a consequence of the use of the programs. It would appear, therefore, that the misconceptions exposed by these pre-A level tasks was possibly not a major factor in learning about the light-dependent reaction of photosynthesis when either *Photosynthesis Explorer* or *Cells and Energy* program were used. Additional support for this point of view was provided by the correlation statistics.

5.7.9 Overview

This Chapter has revealed that the programs promoted the development of an understanding about the light-dependent reaction of photosynthesis, but that overall they generated very little difference in participant performance overall, as judged by the test results. Whilst the outcomes appeared to be very similar, they revealed nothing about the features of the programs that encouraged learning when participants used them. Since the multimedia programs were different in type and in the quantity of feedback, evidence was sought to provide answers to the questions: Were simulations of practical exercises valuable? Was feedback effective and if so of what kind? Was their evidence in support of Laurillard's Discourse Model of Learning? Answers to these questions are developed in the following Chapters by interrogating events during cognitive walkthroughs and by analysing individual responses to the tasks in the Task Booklet. However, another measure of the effectiveness or indeed the efficiency by which learning is achieved is the time taken to realise it. This aspect is explored in the next section of the present chapter.

5.8 Time spent by participants on the programs

5.8.1 Results

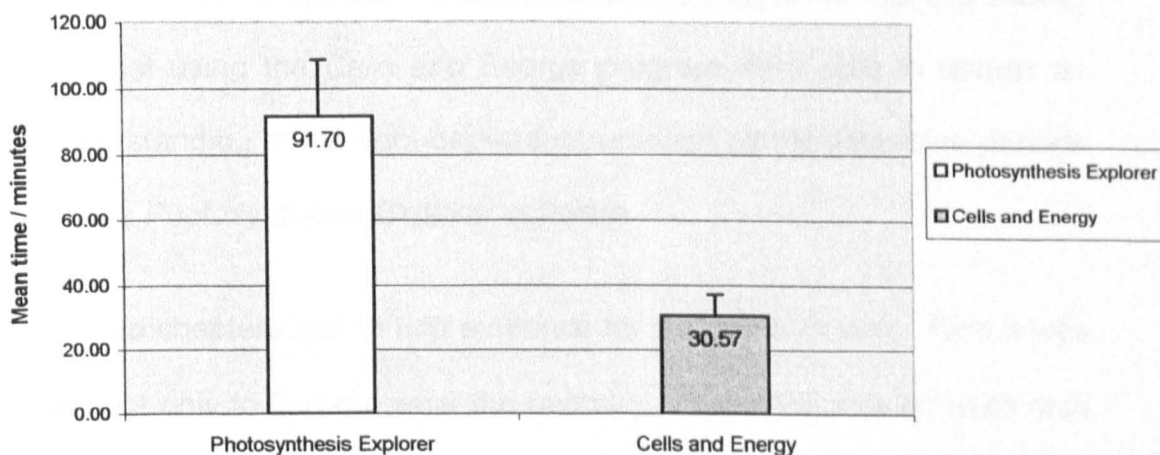


Figure 5.13 Bar chart of comparative mean time to complete sections on the light-dependent reactions for each of two programs

The average mean time for participants who used the *Photosynthesis Explorer* program was 91.70 minutes and for those who used *Cells and Energy* it was 30.57 minutes. These results are shown in (Figure 5.13). For participants who used *Photosynthesis Explorer*, the minimum time for completion was 73.40 minutes and the maximum was 118.60, which was almost 2 hours. For *Cells and Energy*, these times were 18.60 and 41.36 minutes.

5.8.2 Analysis

The mean time for completion of the relevant elements of *Photosynthesis Explorer* was almost three times that of the *Cells and Energy* program. There was no overlap between these data either and even the slowest pair to

complete the relevant section of the *Cells and Energy* software was over half an hour faster than the fastest pair who used *Photosynthesis Explorer*.

5.8.3 Discussion

This evidence and the previous statistical analysis suggested that the shorter periods spent using the *Cells and Energy* program were able to deliver as much understanding of the light-dependent reaction as the extensive periods spent on the *Photosynthesis Explorer* software.

The next two chapters aim to find evidence for the reasons why. First it was important not only to find out what the overall performance was on each task in each test, but also to classify this performance in some way so that the changes in understanding could be compared across the three tests. Whilst overall scores are important measures of performance, they do not inform either about consistency of improvement from pre-test to post-test and from post-test to delayed-post-test or about the performance of individuals. Therefore, second, it was important to obtain measures of 'consistency of improvement' as well as for other categories so that individual numerical responses and those of each group that used each program could be judged for each task across the three tests. Third, it was important to add another support to the classification, which was the written response to each task. This is the focus of Chapter 6. Chapter 7 seeks to find evidence as to why the *Cells and Energy* program is so much more efficient in effecting change, using evidence from cognitive walkthroughs, hypercam, video data and audio recordings.

Chapter 6 Participants' numerical performance on A-level tasks

6.0 Introduction

Participants revealed significant improvements in overall performance as a result of the use of either the *Photosynthesis Explorer* or *Cells and Energy* programs. These improvements were evident whether the ordinal or cognitive scales were applied. Statistical analysis also suggested that the overall performance of the participants was similar whichever scale was employed as the measure of performance. The only difference suggested was that the programs were a secondary factor in the determination of performance from the pre-to post-test stage, but only where the cognitive scale was used.

This overall performance is a useful measure of knowledge and understanding, but in order to explore the effectiveness of the two programs further, it was important to consider the numerical scores on each question for the whole group for each program.

In this Chapter, question performance will be explored by examining both the scores on each of the tasks for all participants at each stage of the testing process and the trends across all the tests. The first approach aids in the determination of two specific features of each cohort that used the different programs. First, initial general understanding of a particular aspect of the light-dependent reaction and second any changes that occurred at the post- and delayed post-test stages as a result of the use of either program. The second approach enables the determination of consistency of learning or lack of it over time.

This exploration is pursued using both the ordinal and cognitive scores. Whilst the statistical tests showed that both measures generated similar results, the cognitive scores were able to show highly confident levels of understanding held by participants, which could not be represented by the ordinal scores alone. However, these cognitive scores could not deliver other representations of other events, such as no learning and improvements in the post-test only, which are also important ways of describing change.

6.1 Rationale

In order to discover the pattern of response to each question it was necessary to follow initially a two-stage procedure. First, to calculate the total scores for all participants' responses to each question in each of the tests and second to categorise the trends from pre- to delayed post-test. This procedure was undertaken both for the 1-12 classification system using the confidence scale and for the level of cognition that only recognised responses as being correct if they held a confidence rating of 60% or above.

The first stage produced data that made possible a graphical presentation of the overall trends and patterns (a broad brush approach) and, second, data that enabled common trends to be grouped together and presented as tables from pre- to delayed post-test.

For the 1-12 classification system, this second procedure required the scores for every participant on each question across the three tests to be placed in one of four categories. For the confidence rating of 60%+ only two categories were possible. By using the data in this way, it was possible to determine the

homogeneity of response or lack of it for each question. For example, it would be quite possible for a particular graphical profile showing higher scores from pre- to delayed post-test to be the result of a very heterogeneous mix of responses from the participants or of consistent higher scores for all or, more likely, a mix.

6.2 Procedure

6.2.1 Ordinal scale

Each participant was given of score of 1-12 for each task. Each task value was then totalled for all participants for each of the tests. This was repeated for all the questions. These scores were then converted into percentages for comparative purposes, since the number of respondents to the delayed post-test questions was only 18 and not 20 as in the pre- and post-tests for *Cells and Energy* and for all the tests for participants using *Photosynthesis Explore*. The results were then presented as bar charts.

In addition, for tabulation, the raw scores (1-12) from pre- to delayed post-test were then considered for each individual question for trends and patterns. The following procedure was followed. Responses were grouped as four categories:

1. Consistently improved events, where the post-test and delayed post-test scores were greater than that of the pre-test.
2. Improvement in post-test events only, where the post-test score was higher than the pre-test, but the delayed post-test score was equal to or less than the pre-test.

3. High consistent scores (possibly considered as no learning events) where the scores were consistently high (8 or more) or showed no gain in the post-test but one in the delayed post-test – characteristically 10-10-11.
4. No learning events where the scores decreased from pre- to delayed-post-test or they were erratic, with a fall in the post-test and an increase in the delayed-post-test.

All the events of each type were then added together to produce 20 response events for *Photosynthesis Explorer* and 18 for *Cells and Energy*.

The consistently improved events were then re-considered so that a number of them were re-classified as high consistent improved events. These were responses where participants showed responses that were consistently more confident in their responses by obtaining a score of 3 or more above the pre-test score. A typical score was 9-12-12. In fact, these high consistent improvers always scored more than 7 on a post- or delayed-post-test question, so that a score of 5-8-8 was still considered a high consistent improver.

6.2.2 Cognitive scale

Each participant was given of score of 1 for each correct response at 60% or above and nothing for any other score whether correct or not. Each task value was then totalled for all participants for each of the tests. This was repeated for all the tasks. These scores were then converted into percentages, and data presented, as for the ordinal scale.

In addition, for tabulation, the confidence ratings from pre- to delayed post-test were then considered for each question for every participant. The following procedure was adopted. Each correct response at a level of 60% or above in the raw data tables was highlighted. Where responses of 60% or more in both the post- and delayed post-test were recorded, together with a pre-test score of 40% or less, then a consistent improvement was noted. These consistent improvement events were totalled for each question.

6.3 Results

The results are presented as bar charts and tables, which enables comparison of the performance of participants on the tasks. Each chart was assembled by topic cover, as was Table 6.1, since this was the most appropriate way to demonstrate the effectiveness of each program's delivery of an understanding of the light-dependent reaction. Questions 1 to 4 (Group A) were on chloroplast structure, 5, 6 and 7 on light energy and the response of chlorophyll to it (Group B), 8, 9, and 10 on ATP and NADPH production (Group C) and the final five questions (11-15) on the products as well as an overview (Group D).

The number of each task on each chart is presented on the x-axis and the overall percentage score ($\text{Total} / \text{Possible total} \times 100\%$) on the y-axis. However, included in the tables is information about each task, whether it covers material with which participants should have been familiar from their studies in Year 12 (P), whether it is a subject covered by only one of the

programs (O) and finally whether it is covered in their interactive/feedback sections (I/F).

6.3.1 Ordinal scale

The bar charts Figures 6.1 and 6.2 show the ranking (by decreasing post-test score) of the tasks within each group, which facilitate comparison. Two features were immediately apparent. First, the rank of each task in three of the groups was the same – Group A (2, 1, 4, 3), Group C (9, 10, 8) and Group D (14, 15, 12, 13, 11) regardless of the program used. The only difference was in Group B where the order of the ranked tasks for *Photosynthesis Explorer* users was 6, 5 and 7, whereas for *Cells and Energy* users the position of Tasks 5 and 6 were exchanged. Second, the general reduction in delayed post-test score subsequent to a high post-test result. Other, though less obvious patterns, were exhibited by the tasks realising the highest post-test scores (in decreasing rank order) for both programs (Tasks 14, 15 and 12 Overview Tasks) and the lowest (in increasing rank order) for *Photosynthesis Explorer* Tasks 8, 3 and 7 and for *Cells and Energy* Tasks 8, 3 and 11 that were, with the exception of Tasks 7 and 11, identical once more.

Other, more specific patterns revealed by the bar charts and described by group were that in Group A participants realised short-term and long-term gains in Tasks 1 and 2, but only in respect of *Cells and Energy* in Task 4 and neither in Task 3. In Group B, *Cells and Energy* participants showed overall

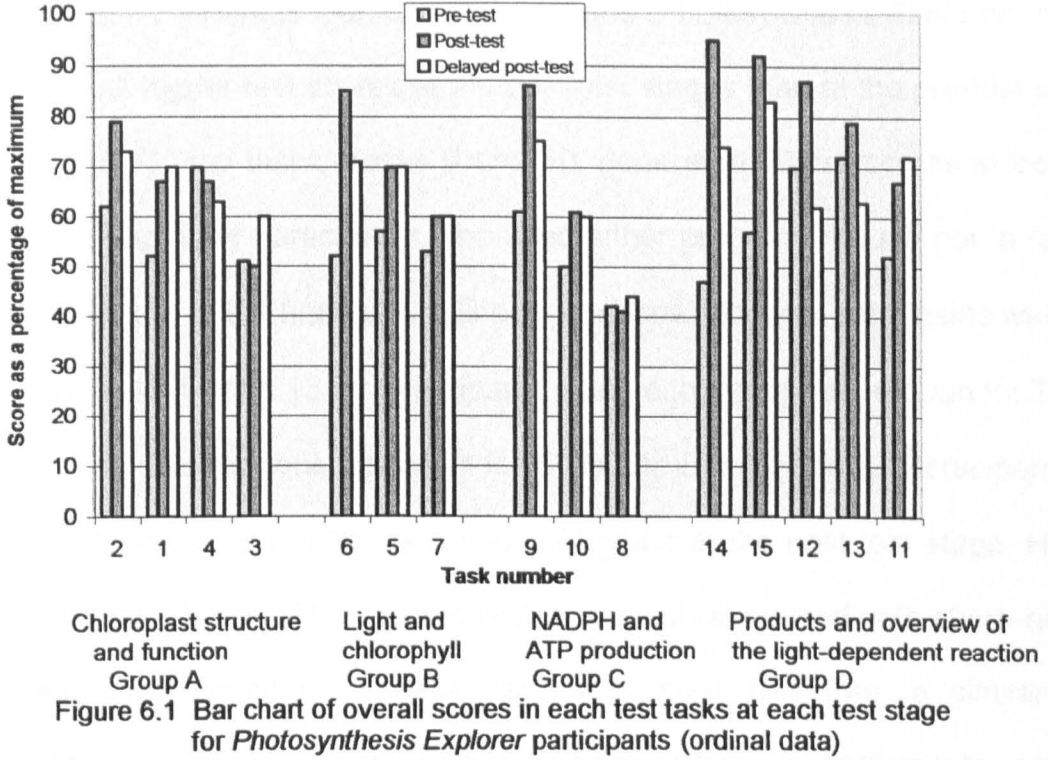


Figure 6.1 Bar chart of overall scores in each test tasks at each test stage for *Photosynthesis Explorer* participants (ordinal data)

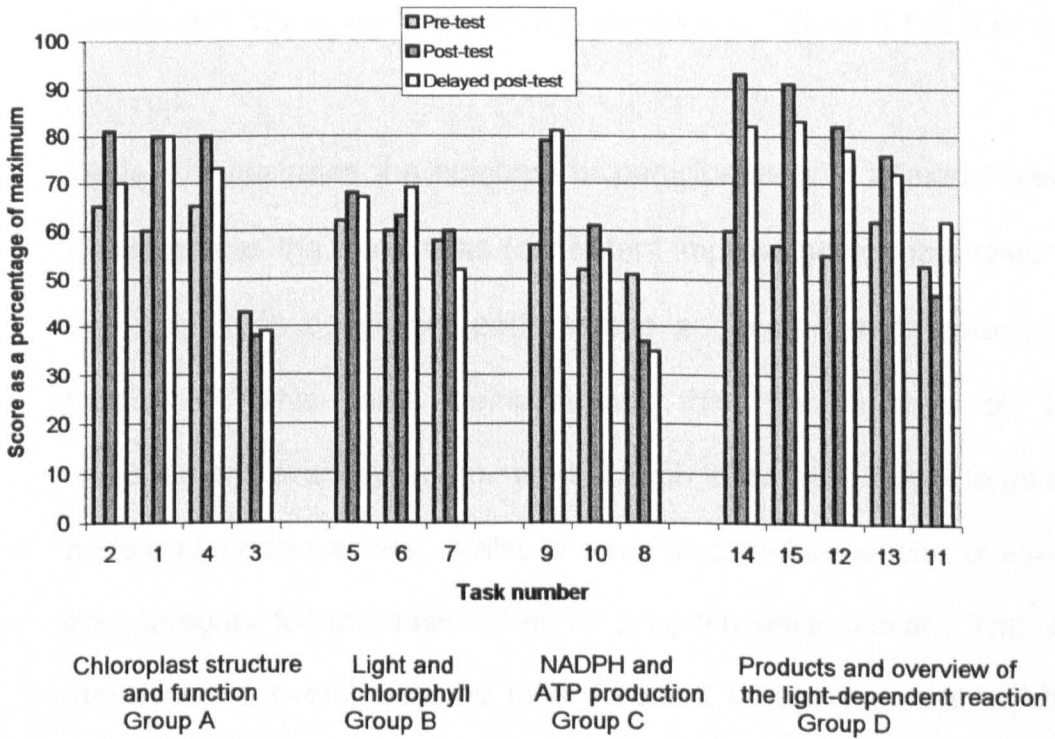


Figure 6.2 Bar chart of overall scores in each test task at each test stage for *Cells and Energy* participants (ordinal data)

very little change in performance across the three tests for any of the tasks (5, 6 and 7), whereas participants who used *Photosynthesis Explorer* realised overall higher test scores at the post-test stages than at the pre-test stage. In Group C, two tasks, Tasks 9 and 10, generated higher scores at both post-test stages for participants who used either program, though not in response to Task 8. In the final group, Group D, short- and long- term gains were made on Tasks 14 and 15 for participants using either program, though for Tasks 12 and 13 this was only apparent for *Cells and Energy* users. Participants using *Photosynthesis Explorer* showed only gains at the post-test stage. However, on Task 11, only *Photosynthesis Explorer* users realised both short- and long-term improvements. These data suggested, therefore, a similar overall response to the same task whichever program participants employed. However, what are the trends when performance is measured across the three tests? These are explored by reference to Tables 6.1 to 6.4.

Table 6.1 illustrates the numbers of participants who demonstrated specific trends across the three tests (consistent improvement, improvement in post-test only, high consistent performance and no learning events) for each program. This table demonstrated that the number of 'consistent improvement' events predominated, though there were also a large number of no learning occurrences. It also showed that the frequencies of events in any one category for any task for either program were similar. The 'consistent improvement event' was the most frequent category in eight of the fifteen tasks for *Photosynthesis Explorer* users and in nine for those who employed the *Cells and Energy* program, six of which were common to both programs.

Nevertheless the 'no learning event' was most frequent for five tasks with *Photosynthesis Explorer* and for six with *Cells and Energy*, four of which were common to both programs. Two somewhat anomalous results, though consistent with the bar chart data, were found for *Photosynthesis Explorer* users where Tasks 12 and 13 generated more responses in the 'improvement in post-test', than in any other, category. There was, therefore, similarity in the overall trends and overall the percentages of 'consistent improvement' events were almost identical at 44% and 43% for *Photosynthesis Explorer* and *Cells and Energy* respectively.

The trends revealed above were further explored by analysis of the numbers of participants placed primarily in the 'consistent improvement' and 'no learning' categories for each task. The task results are described using four groups, A, B, C and D, as for the graphical analysis. In Group A, both programs produced 'consistent improvement' as the most frequent category realised by participants in Tasks 1 and 2. In Task 4, this was only true for users of the *Cells and Energy* program. In Task 3, 'no learning' was most frequent for both programs but only in Task 4 when *Photosynthesis Explorer* was employed. In Group B, Task 6 produced 'consistent improvement' as the most frequent response for users of either program, but only in Task 5 when *Photosynthesis Explorer* was used. Task 7 realised 'no learning' as the most frequent response for those who employed either program. In Group C, Task 9 generated 'consistent improvement' events for most participants whichever program was used, whereas Task 8 realised most responses in the 'no learning' category.

Task group	Task numbers in descending rank order by post-test score for PE (Rank for these tasks for each group shown for CE in brackets)				Number of consistent improvement events		Number of improvements in post-test only events		Number of high consistent performance (no learning?) events		Number of no learning events	
					PE	CE	PE	CE	PE	CE	PE	CE
N = 20 PE N = 18 CE					PE	CE	PE	CE	PE	CE	PE	CE
(A) Chloroplast structure and function	2 (1)		P		10 (7)	6 (4)	4	3	3	4	7	5
	1 (2)		P		9 (6)	8 (5)	1	2	3	6	7	2
	4 (3)		P		5 (2)	8 (4)	3	5	2	3	10	2
	3 (4)			O	5 (4)	2 (-)	2	3	0	0	13	13
(B) Light and chloroplast / chlorophyll response	6 (2)			I/F	11 (8)	8 (5)	6	3	1	1	2	6
	5 (1)			O	10 (3)	6 (2)	3	3	2	1	5	8
	7 (3)			O	7 (2)	3 (1)	4	7	0	1	9	7
(C) NADPH and ATP production	9 (1)			I/F	12 (7)	14 (7)	5	1	2	0	1	3
	10 (2)			I/F	5 (3)	6 (5)	5	3	1	0	9	9
	8 (3)			I/F	4 (3)	1 (-)	1	4	0	0	15	13
(D) Products and overview of the light-dependent reaction	14 (1)			I/F	15 (12)	14 (9)	5	3	0	0	0	1
	15 (2)			I/F	15 (11)	14 (7)	3	2	0	1	2	1
	12 (3)			I/F	7 (4)	11 (8)	8	2	0	2	5	3
	13 (4)			I/F	5 (-)	10 (5)	7	1	4	3	4	4
	11 (5)			I/F	12 (5)	5 (3)	3	2	0	2	5	9

Key Most frequent response Next most frequent response P = topics of likely previous experience O = topic covered by PE only I/F interaction/feedback parts of program
High consistent improvement events bracketed Participants 2B and 4A Included with CE [2A and 4B failed to respond to delayed post-test]

Table 6.1 Data comparing performance on A-level tasks grouped by task topic for *Photosynthesis Explorer* (PE) and *Cells and Energy* programs (CE) (ordinal data)

Accessibility most evident 50%+ consistent improvement					
T. 6 (B) Interaction/ Feedback Light energy and electron transfer [(CE)]	T. 9 (C) Interaction / Feedback ATP production [(L)]	T.14 (D) Interaction / Feedback LDR and the source of oxygen [(L)]		T.15 (D) Interaction /Feedback Overall equation for photosynthesis (L)	
Moderate level of accessibility 35 – 49% consistent improvement					
T. 1 (A) Topic of previous experience Chloroplast design (Either program))	T. 2 (A) Topic of previous experience Site of LDR [(L)]	T.5 (B) Different topics Light energy and wavelengths of light (L)	T. 11 (D) Interaction / Feedback Interdependence of LDR and LIR (L)	T.12 (D) Interaction / Feedback Products of LDR (CE)	T.13 (D) Interaction /Feedback Products and high energy molecules (CE)
Low level of accessibility 20 –34% (no learning most frequent) * except for Task 4					
T. 4 (A) Topic of previous experience Location of light harvesting units (CE)		T. 7 (B) Different topics / Interaction / Feedback The Hill reaction (L)		T.10 (C) Interaction / Feedback NADPH production (Either program)	
Lowest level of accessibility 10 – 19% (no learning most frequent)					
T. 3 (A) Different topics Function of light harvesting units (L)			T. 8 (C) Interaction /Feedback Electron transfer, proton movement and pH (L)		

Key [(L)] PE program promotes more consistent improvement (CI) events, where CI is the most frequent trend for both program users

[(CE)] CE program promotes more CI events, where CI is the most frequent trend for both program users

(L) PE program promotes more CI events, where CI is not the most frequent category for both program users

(CE) CE program promotes more CI events, where CI is not the most frequent category for both program users



Highest gains



Moderate gains



Low/Lowest gains

LDR = light-dependent reaction LIR = light-independent reaction

Table 6.2 Hierarchical presentation of the quality of responses to each of fifteen tasks using ordinal data

Task 10 showed a large minority in this category also, independent of the program used. Finally, in Group D Tasks 14 and 15 showed 'consistent improvement' events demonstrated by most participants whichever program was employed, whereas for Tasks 12 and 13 this applied only to users of *Cells and Energy*. Most *Photosynthesis Explorer* users demonstrated 'improvement in the post-test' only. Task 11 produced most events in the 'consistent improvement' category for *Photosynthesis Explorer* and in the 'no learning' category for *Cells and Energy*.

Table 6.2 summarises the relative level of performance of participants on each task, based on the data from Table 6.1, so that overall accessibility* of the tasks and similarities between the responses of the two groups of participants (cohorts) could be compared. The percentages of consistent improvements on each task for participants using the programs were added together and a mean average value obtained. Four levels were suggested by participants' responses, which were > 50%, 35-49%, 20-34% and 10-29%. At the highest level, were Tasks 6 (Group B), 9 (Group C), 14 and 15 (Group D). At the next level, were Tasks 1 and 2 (Group A), 5 (Group B), 11, 12 and 13 (Group D). At the penultimate level, were Tasks 4 (Group A), 7 (Group B) and Task 10 (Group C). Finally, at the lowest level were Tasks 3 (Group A) and 8 (Group C).

Whilst this analysis highlights the similarities of the two cohorts, what of the differences? Tables 6.1 and 6.2 suggested that overall participants showed

* Accessibility refers to ability of participants to target correct responses as a result of using either program

some differences in trends on some tasks (relative frequencies of response in Table 6.1 and parenthesised notation (L) and (CE) in Table 6.2). These were Tasks 3, 4, 5, 7, 8, 11,12 and 13, which were explored further by ranking the number of 'consistent improvement' events for all the tasks in decreasing order for each program. These results are displayed in Tables 6.3 and 6.4. *Cells and Energy* users were ranked lower on Tasks 2, 3, 5, 7 and 11 whereas *Cells and Energy* users realised higher ranks on Tasks 4, 10, 12 and

Rank	PE Responses	CE Responses
1	14	14
2	15	9
3	9	15
4	11	12
5	6	13
6	2	6
7	5	1
8	1	4
9	12	2
10	7	10
11	3	5
12	10	11
13	4	7
14	13	3
15	8	8

Table 6.3 Ranking of consistent improvement events illustrating falls in rank (2 or more) from *Photosynthesis Explorer* [PE] to *Cells and Energy* [CE] users

Rank	PE Responses	CE Responses
1	14	14
2	15	9
3	9	15
4	11	12
5	6	13
6	2	6
7	5	1
8	1	4
9	12	2
10	7	10
11	3	5
12	10	11
13	4	7
14	13	3
15	8	8

Table 6.4 Ranking of consistent improvement events illustrating gains in rank (2 or more) from *Photosynthesis Explorer* [PE] to *Cells and Energy* [CE] users

13. Task 8 did not change rank because participants performed less well on this task than on any other. Ranking did however suggest a lower order 'consistent improvement' on Task 2 for *Cells and Energy* users and on Task 10 for *Photosynthesis Explorer* as well. Whilst explanations for the similarities and differences are discussed later, comment is required at this stage in explanation for three of the differences. The lower ranking for Tasks 3, 5 and 7 was possibly caused by the content of the two programs. Task 3 was concerned with the need for two light harvesting units, Task 5 with light quality and Task 7 with the Hill reaction. These aspects were not covered in the *Cells and Energy* program.

6.3.2 Cognitive scale

The bar charts (Figures 6.3 and 6.4) show the ranking (by decreasing post-test score) of the tasks within each group facilitating comparison. The levels of knowledge and understanding amongst the stages of the testing process on each task were very distinctive, much more so than when the ordinal scale was used. A number of features were immediately apparent. First, the rank of each task in all four groups was the same – Group A (2, 1, 4, 3), Group B (6, 5, 7), Group C (9, 10, 8) and Group D (14, 15, 12, 13, 11) regardless of the

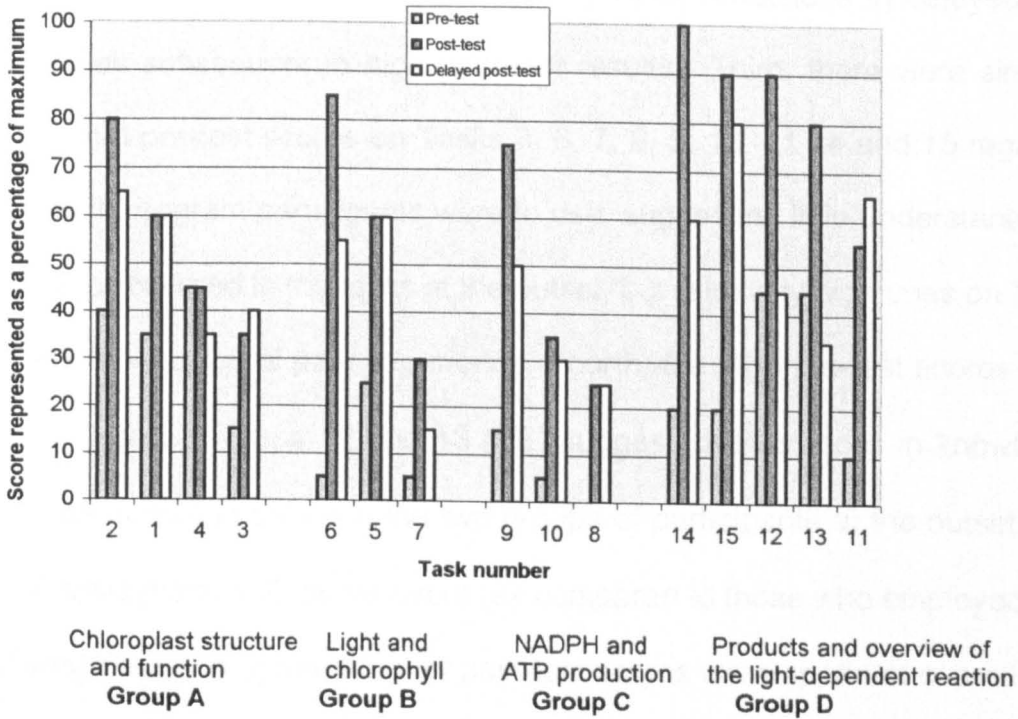


Figure 6.3. Bar chart of overall scores in each test task at each stage for *Photosynthesis Explorer* participants (cognitive data)

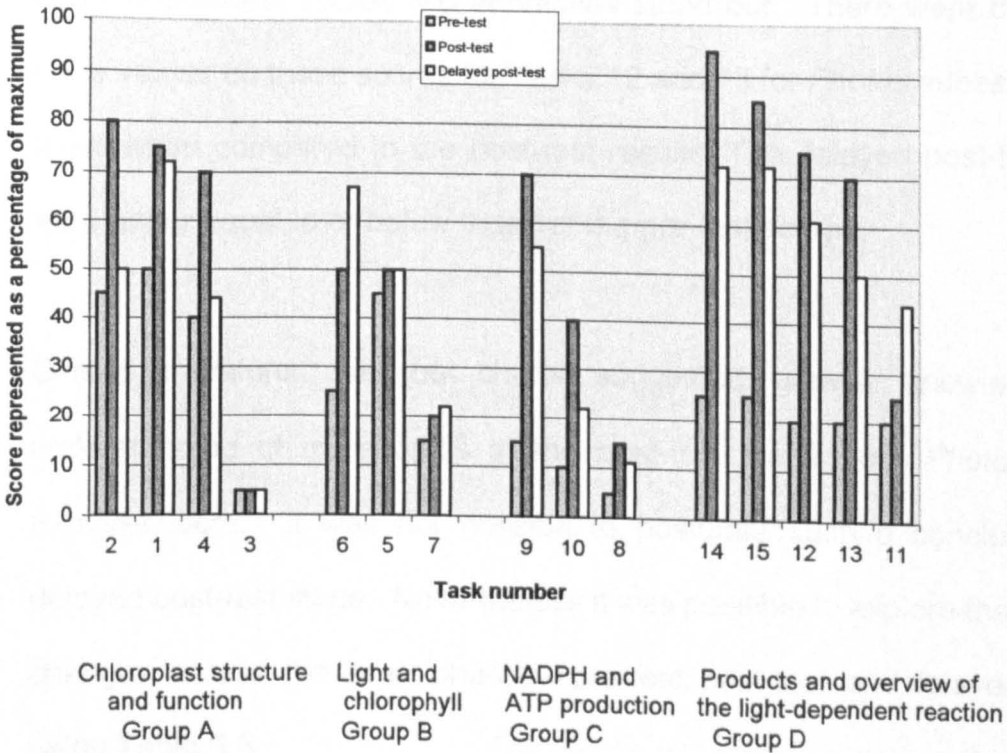


Figure 6.4. Bar chart of overall scores in each test task at each test stage for *Cells and Energy* participants (cognitive data)

program used. Second, there were general reductions in delayed post-test scores subsequent to high post-test results. Third, there were similarly low overall pre-test scores on Tasks 3, 6, 7, 8, 9, 10, 11, 14 and 15 regardless of which program participants were to use, suggesting little understanding of the topics covered in the tasks at the outset, but relatively high ones on Tasks 1, 2 and 4 – topics of past experience. Fourth, the high pre-test scores in Task 5 (CE) and in Tasks 12 and 13 (PE) suggested differences in knowledge and understanding between the two groups of participants at the outset. Fifth, for *Photosynthesis Explorer* users (as compared to those who employed the *Cells and Energy* program), higher post-test scores were apparent overall on Tasks 14, 15, 6, 12, 13, 9, 5, 11, 3, 7 and 8 (in decreasing rank order for PE). Only on Tasks 1, 4 and 10 was this situation reversed. Finally, with regard to the delayed post-test scores two anomalies stood out. There were distinctively lower values on these scores for Tasks 12 and 13 for *Photosynthesis Explorer* users when compared to the post-test results. The delayed post-test scores were either equal to or below those of the pre-test scores.

Overall, therefore, the bar charts suggested greater knowledge and understanding of more topics at the post-test stage for *Photosynthesis Explorer* users. It was not possible to postulate such a conclusion at the delayed post-test stage. Nevertheless it was possible to explore the long-term changes across the three phases – pre-test, post-test and delayed post-test using Table 6.5.

Task group	Task numbers in descending post-test rank order for PE (Rank for these questions in each group shown for CE in brackets)				Number of consistently improved events		Percentage of consistently improved events	
					PE	CE	PE	CE
N = 20 PE N = 18 CE								
A Chloroplast structure and function	2 (1)	P			8	2	40 •	11
	1 (2)	P			6	3	30 •	17
	4 (3)	P			2	3	10	17 •
	3 (4)		O		3	0	15 •	0
	Mean					5 (4.75)	2 (2.00)	24
B Light and chloroplast / chlorophyll response	6 (1)			I/F	9	5	50 •	28
	5 (2)		O		5	2	25 •	11
	7 (3)		O		1	1	5	6 •
	Mean					5	3	27
C NADPH and ATP production	9 (1)			I/F	7	7	35	39 •
	10 (2)			I/F	2	3	10	17 •
	8 (3)			I/F	3	1	15 •	6
	Mean					4	4	20
D Products and overview of the light-dependent reaction	14 (1)			I/F	10	9	50	50
	15 (2)			I/F	11	8	55 •	44
	12 (3)			I/F	5	6	25	33 •
	13 (4)			I/F	1	5	5	28 •
	11 (5)			I/F	9	2	45 •	11
	Mean					7	6	36

Key • Most frequent category

Means calculated to nearest whole number

Table 6.5 Data showing consistent improvement of performance for all participants using either *Photosynthesis Explorer* and *Cells and Energy* programs (cognitive data)

When using the *Photosynthesis Explorer* program only 27% of participants achieved 'consistent improvement' events, consisting of 24%, 27%, 20% and 35% on Group A, B, C and D tasks. An even smaller percentage (21%) reached this level from 11%, 15%, 21% and 33% when the *Cells and Energy* program was used. The differences between the overall percentages arose from participant performance on tasks in Group A and Group B, where *Cells and Energy* users achieved generally lower percentage values. A higher percentage of *Photosynthesis Explorer* users realised 'consistent improvement' events on Tasks 1, 2, 3 (Group A) 5, 6 (Group B), 8 (Group C), 11 and 15 (Group D) and for *Cells and Energy* users on Tasks 4 (Group A), [7] (Group B), [9] and 10 (Group C), 12 and 13 (Group D). These results suggested the cohort that employed *Photosynthesis Explorer* held a sound understanding of more topics than that using the *Cells and Energy* program. Nevertheless if the tasks of past experience (Tasks 1, 2 and 4) and of different topic cover (Task 3 and 5), included in the list above, are removed from the equation, then the number of tasks favoured by one cohort or the other is four (Tasks 6, 8, 11 and 15 for *Photosynthesis Explorer* and Tasks [9], 10, 12 and 13 for *Cells and Energy*). These, along with Task 14, cover topics on the interactive feedback parts of the programs. Although, as was suggested at the outset, there was almost overall equivalence between the cohort performance in Group C and D tasks (with a bias towards *Photosynthesis Explorer* users if Task 6 – also secured in the interactive/feedback parts of the programs – was included) there was considerable variation between the cohort performances on the different tasks. In order to look at the relative performance (in terms of 'consistent improvement' events) of the tasks, tables

were prepared similar to those for the ordinal data. Table 6.6 ranked the overall participant performance on tasks, so that overall accessibility of the tasks and similarities between the responses of the two cohorts could be compared. Tables 6.7 and 6.8 ranked them for each of the programs independently, so that their relative accessibility for each cohort of participants could be compared.

An explanation of the ranking procedure is required first, especially for Table 6.6. Percentages of consistent improvements on each task for participants using the programs were added together and a mean average value obtained. Performances were then assigned to four levels at > 35%, 25-34%, 10-24% and <10%. In the other tables, 'consistent improvements' events were ranked in descending order for each program independently, so that differences could be explored more fully.

Tasks 6, 9, 14 and 15 were the most accessible overall, all of which were in the interactive/feedback parts of either program. Tasks 1, 2, 11 and 12 were moderately accessible, two of which (11 and 12) were in the interactive/feedback section and the other two were topics of past experience. Low accessibility was found in Tasks 4, 5, 8, 10 and 13, three of which (8, 10 and 13) were in the interactive/feedback sections and the other two Tasks 4 and 5 involved topics of past experience and different topic cover respectively. The lowest level of accessibility was found to be in Tasks 3 and 7 (different topic cover).

Accessibility most evident > 35% consistent improvement events				
T. 6 (B) Interaction /Feedback Light energy and electron transfer (L)	T. 9 (C) Interaction / Feedback ATP production (Either program)	T.14 (D) Interaction / Feedback LDR and the source of oxygen (Either program)	T.15 (D) Interaction / Feedback Overall equation for photosynthesis (L)	
Moderate level of accessibility 25 – 34% consistent improvement events				
T. 1 (A) Topic of previous experience Chloroplast design [(L)]	T. 2 (A) Topic of previous experience Site of the LDR (L)	T. 11 (D) Interaction / Feedback Interdependence of LDR and LIR (L)	T. 12 (D) Interaction /Feedback Products of the LDR [(CE)]	
Low level of accessibility 10 – 24% consistent improvement events				
T. 4 (A) Topic of previous experience Location of light harvesting units [(CE)]	T. 5 (B) Different topics Light energy and wavelengths of light (L)	T. 8 (C) Interaction / Feedback Electron transfer, proton movement and pH (L)	T.10 (C) Interaction / Feedback NAPH production (CE)	T.13 (D) Interaction / Feedback Products and high energy molecules [(CE)]
Lowest level of accessibility < 10% consistent improvement events				
T. 3 (A) Different topics Function of light harvesting units (L)			T. 7 (B) Different topics / Interactive / Feedback The Hill reaction (Either)	




Key [(CE)] Percentage consistent improvement events for CE above PE by 6-10%
 (CE) Percentage consistent improvement events for CE above PE by >10%  Highest gains  Moderate gains  Lower/Lowest gains
 (L) Percentage consistent improvement events for PE above CE by >10%
 (Either) Percentage consistent improvement events equal or difference between 0-5% LDR = light-dependent reaction LIR = light-independent reaction

Table 6.6 Hierarchical presentation of the quality of responses to each of fifteen tasks using cognitive data

Rank (PE)	PE Task Numbers	CE Task Numbers	Rank (CE)
1	15	14	1
2=	6	15	2
2=	14	9	3
4	11	12	4
5	2	6	5=
6	9	13	5=
7	1	1	7=
8=	5	4	7=
8=	12	10	7=
10=	3	2	10=
10=	8	5	10=
12=	4	11	10=
12=	10	7	13=
14=	7	8	13=
14=	13	3	15

Table 6.7. Ranking of consistent improvement events illustrating falls in rank (two or more) from *Photosynthesis Explorer* [PE] to *Cells and Energy* [CE] users

Rank (PE)	PE Task Numbers	CE Task Numbers	Rank (CE)
1	15	14	1
2	6	15	2
2=	14	9	3
3=	11	12	4
5	2	6	5=
6	9	13	5=
7	1	1	7=
8=	5	4	7=
8=	12	10	7=
10=	3	2	10=
10=	8	5	10=
12=	4	11	10=
13=	7	7	13=
14=	10	8	13=
14=	13	3	15

Table 6.8. Ranking of consistent improvement events illustrating gains in rank (two or more) from *Photosynthesis Explorer* [PE] to *Cells and Energy* [CE] users

The ranked data suggested that overall participants who used *Photosynthesis Explorer* performed better long-term on Tasks 2, 3, 5, 6, 8 and 11 and for those who employed *Cells and Energy* the Tasks were 4, 9, 10, 12 and 13.

6.4 Discussion

This discussion commences with a summary of the main trends and patterns as revealed in the results section. This is followed by suggestions as to the extent of learning about the light-dependent reaction of photosynthesis from these overall trends and patterns, both overall and from the perspective of the different programs employed.

It was possible that the various levels of accessibility in the post-test reflected the ability of the programs to engender an understanding of the tasks. Nevertheless whilst this may be so, it may not reflect participants' understanding of processes or concepts. Thus, whilst accessibility is discussed below, low levels, for example, may not reflect any deficiencies in either of the programs or both, but rather inherent difficulties of the tasks themselves. Nevertheless for the purpose of this discussion, accessibility was used as a measure of learning or understanding about the concept that each task endeavoured to elicit. Discussion about the difficulty or facility of the tasks is addressed in Chapter 8.

The higher gains in the immediate post-test scores by users of *Photosynthesis Explorer* were only partially transferred into more long-term gains compared to the cohort that used the *Cells and Energy* program. The most obvious feature about the data as a whole was how similarly both groups of participants performed.

Overall the highest level of accessibility was on Tasks 6, 9, 14 and 15, which ever measure (ordinal or cognitive) was used. It may be concluded, therefore that many participants held long-term sound understanding about:

- loss of electrons from chlorophyll initially (Task 6);
- proton movement and ATP synthesis (Task 9);
- water splitting and the source of oxygen (Task 14);
- the overall equation of photosynthesis (Task 15).

At the intermediate level of accessibility Tasks 1, 2, 5, 11, 12 and 13 were included when the ordinal scale was applied, though the cognitive scale suggested that participants performed even less well on Tasks 5* and 13*. So at this intermediate level, fewer participants held a long-term understanding about:

- chloroplast design (Task 1);
- the site of the light-dependent reaction (Task 2);
- wavelength energy and photosynthesis (Task 5)*;
- the interdependence of the two phases of photosynthesis – the light-dependent and -independent phases (Task 11);
- products of the light-dependent phase (Task 12);
- energy content of products of the light-dependent phase (Task 13)*.

* Assigned the rank at which it first appeared, whether it was ordinal or cognitive data

At an even lower level, Tasks 4, 7 and 10 were included using the ordinal scale, and in addition Tasks 5 and 13, already referred to on the cognitive scale, and Task 8*. The cognitive scale suggested that Task 7* was at the lowest level of accessibility. So at this penultimate level of accessibility, the data suggested that fewer participants possessed an understanding about:

- position of light harvesting units in chloroplast (Task 4);
- the Hill reaction (Task 7*);
- electron transfer in membrane and proton movement across it (Task 8*);
- use of electrons and protons in the production of reduced co-enzyme Task 10);

Finally at the lowest level of accessibility stood Task 3 whatever the scale of measurement. There were, therefore, very few participants who understood about:

- chloroplast membranes containing two light harvesting units (Task 3).

Whilst there were occasional differences presented in this analysis as to the levels of overall performance (Tasks 5, 7, 8 and 13) using the two methods of measuring long-term gain, they were largely the same. In the following chapter (correlating scores with written comment) the cognitive scale was used since it was the measure of metacognition, which the ordinal scale was not.

Differences between performances of participants who used the alternative programs were explored next. This was considered through the level of overall achievement on each task as listed above.

At the highest level (where numerical data suggested the highest number of participants achieved long-term understanding) on Tasks 6, 9, 14 and 15, using the ordinal scale, there appeared to be little difference in the performance of either cohort whichever program was employed. Differences were, however, apparent at the metacognitive level on Tasks 6 and 9 when the ranking procedure was applied (PE higher rank for Task 6 and CE for Task 9). Though recourse to Table 6.5 showed that the higher rank in this case did not justify such a conclusion for Task 9, since the percentages of 'consistent improvement events were very little different. Task 15 though ranks were very little different, produced much higher 'consistent improvement' events for *Photosynthesis Explorer* users.

At the next level were Tasks 1, 2, 5*, 11, 12 and 13*, with higher ranking for *Photosynthesis Explorer* users on Tasks 2, 5 and 11 on both scales. These were real differences in performance, which were supported by all the data. Task 1 realised a greater proportion of consistent improvement events at the cognitive level for *Photosynthesis Explorer* users, though other data suggested an equivalent performance. For *Cells and Energy* users higher ranks were found on Tasks 12 and 13 with other data supporting more long-term learning, though the 'consistent improvement' cognitive data were not convincing for Task 12.

At the penultimate level were Tasks 4, 7*, 8* and 10. For Tasks 4 and 10, there was evidence of a better performance by CE participants, though only marginally so at the cognitive level. Although Task 8 was the lowest ranking at the ordinal level for both programs, there was evidence both from the number of 'consistent improvement' events for both measures and from the cognitive ranks that *Photosynthesis Explorer* users performed better on this Task. It was also possible to conclude that Task 7 was more accessible for more *Photosynthesis Explorer* users, though the cognitive scale suggests that this was not so.

At the lowest level was Task 3. This task was also more accessible to more *Photosynthesis Explorer* participants. Both the ordinal and cognitive scales demonstrate that this was so.

These overall trends and patterns are summarised in Table 6.9. The differences in 'cognitive' level of performance could reflect the difficulty or facility inherent in the design of the tasks themselves, rather than in their relative accessibility as a result of using one or other of the programs. Whilst this possibility cannot be discounted at this stage, it was considered unlikely for a number of reasons, at least for most tasks. First, a Chief Examiner evaluated tasks for accessibility. Second, most task results that emanated from the different programs differed in both the proportion of consistent improvement events and in the ranking assigned to them. These changed rankings suggested effects due to the running of each program, such as

differences in the programs' delivery and/or content rather than the difficulty of the task per se. Thus on the basis of content alone *Photosynthesis Explorer* participants might have been expected to perform better on Task 5 wavelength energy and photosynthesis, Task 7 the Hill reaction, and Task 3 chloroplast membranes and number of light harvesting units. This they did, though Task 7 was a task of considerable conceptual difficulty (hence no ranking differences at the cognitive level) as will be addressed in the concluding Chapter.

What did these data suggest about the different cohorts' understanding of the light-dependent reaction as a result of the use of these two programs? Many understood an overview of the process – the need to modify the GCSE equation of the process (Task 15) in view of the water splitting process (Task 14). Many also developed an understanding of chloroplast design (Task 1) and the mechanism of ATP synthesis (Task 9). These did not, however, constitute an understanding of the whole process or of its connection to the light-independent phase. Essential for this were consistent improvements on many other tasks as well, but most importantly on Task 2 (the site of the light-dependent reaction), Task 4 (position of the light harvesting units), Task 6 (loss of electrons from chlorophyll), Task 8 (electron transfer in the membrane and proton transfer across it), Task 10 (electrons and protons in the production of NADPH), Task 12 (products of the light-dependent reaction), Task 13 (energy content of the products) and Task 11 (interdependence of the two phases – the light-dependent and -independent reactions) – all fifteen in fact except for Tasks 3, 5 and 7, which means Tasks 1, 2, 4, 6, 8 to 15.

Both programs had a moderate and different impact on a number of these Tasks. *Photosynthesis Explorer* users were better able to access initial events and the sites at which these occur (Tasks 2, 6), though with some evidence of greater assistance in one intermediate event (Task 8), but the access to it by either cohort was very low. In addition, they were better able to make the link between the two phases of photosynthesis (Task 11).

On the other hand, data suggested *Cells and Energy* users were more proficient in accessing Tasks that were concerned with the intermediate events in the process – those that were concerned with proton and electron movements (Task 10) and with products released as a result of these events (Tasks 12 and 13). Though these data differences are not so clearly differentiated as with the *Photosynthesis Explorer* cohort.

A pattern emerged here suggesting that neither program provided sufficient change during the period of the investigation to conclude that they were effective in delivering an overall understanding of the light-dependent reaction of photosynthesis, rather than just parts of it. Whilst there was numerical evidence that no task (other than possibly Task 3 for *Cells and Energy* users).

Cognitive levels	Question number (chronological for each level)	Topic cover	P/ O/ I/F	Evidence of similarity/difference in proportion of consistent improvements or rank				Tasks with different proportions of consistent improvements and ranks at Cognitive and Ordinal values		Tasks with different proportions of consistent improvements at Cognitive and Ordinal values, but ranks only at Cognitive values	Tasks with different proportions of consistent improvements on Cognitive value, but no other differences	Tasks with no differences / miscellaneous
				Cognitive performance Same (S) Different (D)	Ordinal performance Same (S) Different (D)	Cognitive rank Same/Similar (S) Different (D)	Ordinal rank Same/Similar (S) Different (D)					
1	6	Loss of electrons from chlorophyll initially	I/F	D/PE	D/PE	D/PE	S		✓ PE			
	9	Proton movement and ATP synthesis	I/F	D/CE/S	D/CE	D/CE	S		✓ CE			
	14	Water splitting and the source of oxygen	I/F	S	S	S	S				✓	
	15	The overall equation for photosynthesis	I/F	D/PE	S	S	S			✓ PE		
2	1	Chloroplast design	P	D/PE	S	S	S				✓ PE	
	2	The site of the LDR	P	D/PE	D/PE	D/PE	D/PE		✓ PE			
	5	Wavelength energy and photosynthesis	O	D/PE	D/PE	D/PE	D/PE		✓ PE			
	11	Interdependence of the two phases – LDR and LIR	I/F	D/PE	D/PE	D/PE	D/PE		✓ PE			
	12	Products of the LDR	I/F	D/CE	D/CE	D/CE	D/CE		✓ CE			
	13	Energy content of the products of LDR	I/F	D/CE	D/CE	D/CE	D/CE		✓ CE			
3	4	Position of light harvesting units	P	D/CE	D/CE	D/CE	D/CE		✓ CE			
	7	The Hill reaction	O	D/CE/S	D/PE	S	D/PE				M	
	10	Electrons and protons in the production of NADPH	I/F	D/CE	D/CE	D/CE	D/CE		✓ CE			
4	3	Chloroplast membranes contain two light harvesting units	O	D/PE	D/PE	D/PE	D/PE		✓ PE			
	8	Electron transfer in membrane and transfer of protons across it	I/F	D/PE	D/PE	D/PE	S		✓ PE			

Table 6.9 Overall similarities and differences between overall consistent improvement events and relative ranking of responses

Key D/PE Higher performance by *Photosynthesis Explorer* participants D/CE Higher performance by *Cells and Energy* participants

Marked differences	Other differences	Marked similarities	Other similarities	Miscellaneous
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was inaccessible to the cohort as a whole, there was the possibility that some participants were capable of gaining this understanding when either program was employed.

As a first step in determining whether this was the case, it was important to obtain corroborative evidence for the validity of participants' numerical responses to the Tasks. This was undertaken by relating these responses to written comments, which in turn were checked against the target statement to each task. At the same time and as a prelude to offering suggestions as to why some participants were more or less successful when using either of these programs, it was important to undertake this not only for high scoring participants but for other members of each cohort, too. These are the topics of Chapter 7.

Chapter 7 Correlations of scores and written comment and understanding of the light-dependent reaction

7.1 Introduction

Evidence was sought in this Chapter for validation of the changed scores in the tasks at the post-test stages as a representation of improved knowledge and understanding of the light-dependent reaction of photosynthesis. Validation was achieved by relating participant choice and confidence rating to written comment on each task. Pairs of participants were selected for this validation process through the use of the ordinal and cognitive scales. This was undertaken first for one pair of participants who achieved high numbers of consistent improvement events on one or other of the programs in order to answer the question, 'Is it possible for either of the programs to deliver an understanding of the light-dependent reaction'? Next, one pair of participants from each of a mixed scoring partnership and a low one was selected in order to provide further validation of the relationship between the scores obtained and their comments on each task. These operations were carried out not only as a validation of the numerical scores, but also as material evidence to correlate with the content of, and interaction and feedback within, the programs, as well as with the activities of the participants and researcher during the running of the programs. These are discussed in Chapter 8. In addition, participant comment was used to identify misconceptions at the start and dispelled or created by the use of either program.

7.2 Procedure

First the number of consistent improvement events using the ordinal scale was obtained for each participant for each program. On the basis of these

scores, pairs of participants were assigned to three groups: high, mixed and low scoring. This exercise was repeated for the cognitive scale and where participants demonstrated high, mixed and low scoring characteristics on both scales, they were also assigned to one of three groups. With the *Cells and Energy* participants it was not always possible to assign pairs to the mixed and low scoring partnerships on the cognitive scale, so that additional evidence was sought. If members of one pair obtained low scores at most stages, they were considered to be low scoring and if one obtained high scores at most stages, but the other did not, then this was a mixed pair. For *Photosynthesis Explorer* users, the following pairs were selected: Pair 7 (high scoring), Pair 5 (mixed) and Pair 6 (low). For *Cells and Energy* users, the pairs were Pair 8 (high scoring), Pair 5 (mixed) and Pair 3 (low). These original identifiers are confusing. Therefore for clarity they are re-identified as shown in Table 7.1.

Original identifier of pair	New identifier of pair	Original identifier of participants	New identifier of participants
Pair 7 (PE)	Pair PE1	7A + 7B	P1 + P2
Pair 5 (PE)	Pair PE2	5A + 5B	P3 + P4
Pair 6 (PE)	Pair PE3	6A + 6B	P5 + P6
Pair 8 (CE)	Pair CE4	8A + 8B	C7 + C8
Pair 5 (CE)	Pair CE5	5A + 5B	C9 + C10
Pair 3 (CE)	Pair CE6	3A + 3B	C11 + C12

Table 7.1 Identification of participants

7.3 Results, analysis and discussion

7.3.1 Presentation of raw data

The results were presented as tables (example, Appendix C) in which the participants' actual answers – the designation of response (right or wrong), the confidence of that response and the written comment associated with it –

are displayed. The tables contain highlighted sections, which indicate the confidence of the correct responses. If the correct choice was made at a level at or below 40%, then this warranted a lightly shaded cell, but if at 60% or above then this cognitive level was represented by a darkly shaded cell. Similarly the written comment was treated in the same way, so that if a description carried elements of the target response, then this warranted light shading, but if it contained most of the elements, then this section was highlighted more heavily. Using this approach it was possible to look for correlations between a numerical attribution of the correct selection and the written response associated with it.

7.3.2 Target written responses

The target written responses (Table 7.2) were described in the language of the scientist. They consisted of two or three sentences that contained a summary of the facts that participants might be expected to state in order to demonstrate an understanding of the topic addressed in each task. However, it was not the expectation that participants should make their comments in this scientific language in order to be considered as being in possession of sound understanding, but rather to make them in a form that was clear and unambiguous. Thus if participants made clear statements that explicitly described the meaning inherent in the target response, then sound understanding was considered to be an appropriate designation, even if the whole statement was not provided. If the response lacked specificity, but contained no error, then partial understanding was considered appropriate. If the response was simply a re-statement of a phrase or phrases within a task, was not relevant, was absent or contained reference to the assistance of the

computer alone, then no understanding was most fitting. It was understood that the lack of comment or reference to the aid of the computer could be interpreted in other ways, but since there was no description, this lack of evidence was best be described as 'no understanding'. If, on the other hand, the statement was incorrect, then this was designated a misconception.

These various levels may be demonstrated by using sample responses from Task 6. The statement that 'water releases the electrons and protons' was a clear and unambiguous statement that was sound and not a re-statement of part of the alternatives contained in this task, as was the statement that 'from taking part in the program I think the water is definitely the source of the electron'. On the other hand 'from the program, I remember movement of electrons, but I am unsure as to where the electrons come from' represented a partial understanding only. Such comments as 'very unsure', 'a guess' and 'remembered from the CD' constituted no understanding. Finally 'an electron must be added to water to split it' was a misconception.

7.3.3 Introduction to results, analysis and discussion

A numerical summary of results is presented in Table 7.3 as reference to the overall changes. More detailed results are provided in Tables 7.4 to 7.6 for each participant. The detailed analysis considers the number of correct choices, correlations of scores and written comment for both members of each pair at each level at each stage of the testing process.

Nevertheless it is useful to outline a number of overview points briefly here. Except for Participant C12, the number of correct choices at post-test stages was always higher than before the use of either program. However, even this

participant increased the score in the post-test stage. Goal concepts, partially or fully, were rarely achieved in the pre-test, but much more frequently in subsequent tests, especially in the post-test. Participants P3, P5 and P6, who used *Photosynthesis Explorer* and Participants C9, C11 and C12, who used *Cells and Energy* failed to state a complete goal concept at the delayed post-test stage. Even at a partial level, they rarely achieved the goal. Misconceptions were noted only occasionally and one that appeared more than once – about the source of oxygen - was found in the pre-test for four participants P2, P4, P6 and C10 and in the delayed post-test for C12 only.

The discussion relates trends and patterns and misconceptions to participants' understanding of events in the light-dependent reaction and to an understanding of the whole process, judged by their answers to Tasks 1, 2, 4, 6 and 8 to 15. It also discusses pre-conceptions at the start as well as misconceptions that appeared after the programs' use and any that occurred at the pre-test stage that might affect an understanding of the light-dependent reaction.

7.3.4 Results for high scoring pairs

The most obvious feature of the results for Participants P1 and P2 and C7 and 8 was that on every task, whether at the pre-, post- and delayed post-test stages, written comment accompanied the choices made.

Task Number	Correct choice of response	Target written responses
1.	B Yes	Chlorophyll is found in discrete units that are light harvesting units (LHUs), which funnel trapped energy to a reaction centre. Being spread out on membranes within the chloroplast, there is an increase in the surface that is exposed to light.
2.	B No	The light-dependent reaction requires chlorophyll, which is a constituent of membranes within a chloroplast. Other molecules are required in the light-dependent reaction, which are also held in the thylakoid membranes and electron transfer occurs between chlorophyll and these other molecules.
3.	A Yes	There are two photosystems, PS1 and PS2, each of which is involved in raising electrons to higher energy levels. PS2 receives electrons from water and transfers them to PS1 through the electron transport chain where they are further energised by light energy within PS1.
4.	B Yes	The double membrane that surrounds chloroplasts is not pigmented. Chlorophyll and other pigments are found in LHUs on the granal and inter-granal lamellae.
5.	B No	Shorter wavelength photons contain more energy than those of longer wavelength. Blue light, which has a shorter wavelength, has, therefore, photons of higher energy.
6.	A No	Light does not consist of particles called electrons. Rather the [elementary] particles are called photons. Electrons come from, in the case of photosynthesis, water.
7.	B Yes	In this reaction, electrons donated to DCPIP [to potassium ferricyanide when Hill and his collaborators carried out the original experiments] come from chlorophyll, which in its turn receives them from water. The reaction only proceeds in light when the energy absorbed can be transferred from excited chlorophyll molecules to electron acceptors – water undergoes photolysis and oxygen is released.
8.	A No	Protons are driven from the stroma into the thylakoid space. Increase in protons lowers the pH in the thylakoid space, raising that of the stroma.
9.	A Yes	It is the development of proton gradients that are essential for ATP synthesis. When a gradient reaches a threshold level, protons flow from the thylakoid space into the stroma through membrane proteins. This flow activates the enzyme ATPase that together with the energy released by the flow of protons enables ATP synthesis.
10.	A Yes	<i>Either</i> The answer cannot be B, because NAD^+ is not involved in photosynthesis, but in respiration. Also there are two photosystems [PS1 and PS2]. <i>Or</i> The answer must be A, because NADPH_2 is produced in the light-dependent reaction of photosynthesis. There are two photosystems.
11.	B Yes	The light-independent reaction does not depend on light energy, but it does occur both in the light and dark. The rate of one determines the rate of the other.
12.	A No	The light-dependent reaction produces three products: oxygen, reduced NADP and ATP. Reduced NADP and ATP are used in the light-independent reaction.
13.	A Yes	Only reduced NADP (NADPH , $\text{NADPH} + \text{H}^+$, NADPH_2) and ATP are high-energy molecules. Oxygen may enable energy to be released from compounds, such as hydrogen, hydrocarbons and other organic compounds.
14.	B No	The oxygen comes from water. [The use of the heavy oxygen isotope shows that this is so.] It is not used again [though H^+ , electrons and CO_2 are used later].
15.	B No	The equation is very much simplified. Since the source of oxygen is water, 12 molecules of water are required at the start.

Table 7.2 Target answers to the fifteen A-level tasks

Pair score level	Program	Participants	Test stage	Number of correct responses	Number of highly confident correct responses	Goal concept	Partial goal concept	Number of misconceptions
High scores	P E	P1	Pre-test	10	5	0	5	3
			Post-test	10	8	7	4	2
			D. post-test	14	11	7	7	0
		P2	Pre-test	6	2	0	2	3*
			P.T.	13	11	8	4	3
			D.P.T.	13	11	5	5	0
	C E	C7	Pre-test	9	9	1	5	0
			P.T.	12	12	7	5	0
			D.P.T.	13	13	1	7	0
		C8	Pre-test	9	2	0	2	0
			P.T.	13	9	9 [+1]	0	2 [+1]
			D.P.T.	8	8	5	1	3
Mixed scores	P E	P3 (L)	Pre-test	3	0	0	1	1
			P.T.	9	4	5	2	2
			D.P.T.	9	2	0	1	0
		P4 (H)	Pre-test	5	5	2	1	1/2*
			P.T.	13	13	8	7	0
			D.P.T.	11	11	6	4	1
	C E	C9 (L)	Pre-test	6	1	0	0	0
			P.T.	12	9	2	0	0
			D.P.T.	8	2	0	0	0
		C10 (H)	Pre-test	11	11	0	4	2*
			P.T.	13	13	8	5	1
			D.P.T.	12	12	6	3	0
Low scores	P E	P5	Pre-test	4	2	0	1	3
			P.T.	8	8	3	5	1
			D.P.T.	8	8	0	0	0
		P6	Pre-test	9	1	1	3	4*
			P.T.	9	8	7	4	2
			D.P.T.	9	5	0	0	0
	C E	C11	Pre-test	5	2	0	0	0
			P.T.	11	9	2	2	0
			D.P.T.	6	4	0	2	1
		C12	Pre-test	8	2	0	0	0
			P.T.	10	8	2	5	1
			D.P.T.	6	1	0	1	3*

Table 7.3 Summary of number of correct responses, goal concepts and misconceptions at each of the test stages

* participants with misconception as to the source of oxygen

Program	Participant	Test stage	Tasks				Misconceptions
			Correct responses	Highly confident correct responses	Goal concept	Partial goal concept	
P E	P1	Pre-test	2, 4 – 8, 11, 12, 13, 15	2, 4, 6, 12, 13	None	2, 6, 9, 12, 13	4. The raised dots are grana inside the chloroplasts 5. You are unaffected by UV light 8. Loss of protons doesn't raise the pH
		P.T.	1, 2, 4, 6, 7, 9, 11, 13, 14, 15	1, 2, 4, 6, 11, 13, 14, 15	6, 7, 8, 9, 11, 14, 15,	2, 4, 12, 13	3. One unit does not require light [reference to light harvesting units] 10. NAPH to NADH + H ⁺ not NADPH + H ⁺
		D.P.T.	1 – 7, 9 – 15	1 – 4, 6, 10 – 15	6, 8, 9, 11, 12, 14, 15	1 – 4, 7, 10, 13	None
	P2	Pre-test	4, 6, 7, 9, 11, 13	9, 13	None	11, 13	7. Photosynthesis is one total reaction and cannot be split up into individual parts 14. The oxygen is released and the carbon which stays must be used and therefore carbohydrates must be made 15. The equation cannot balance if it [oxygen] comes from water as water has merely O whereas the oxygen is O ₂
		P.T.	1 – 4, 7 – 15	1 – 3, 7 – 9, 11 – 15	3, 4, 8, 11 – 15	1, 2, 7, 9	5. The red light does have a higher wavelength and the infra-red burns, unlike UV 6. The electron is needed in the light-dependent part of the chloroplast and splits the water, releasing oxygen 10 The two photosystems are in the thylakoid and the NADPH is passed from here to the stroma
		D.P.T.	1, 3, 4, 6 – 15	1, 3, 6, 8 – 15	6, 11, 12, 14, 15	7 – 10, 13	None
C E	C7	Pre-test	1, 2, 4, 6, 9, 10, 12, 13, 15	1, 2, 4, 6, 9, 10, 12, 13, 15	12	1, 2, 4, 13, 15	None
		P.T.	1, 2, 4 – 7, 9, 11 – 15	1, 2, 4 – 7, 9, 11 – 15	4, 6, 7, 9, 12, 14, 15	1, 2, 5, 11, 13	None
		D.P.T.	1, 2, 4 – 9, 11 – 15	1, 2, 4 – 9, 11 – 15	[12]	1, 2, 4, 7, 11, 13, 15	None
	C8	Pre-test	2, 3, 4, 6, 9, 10, 11, 13, 14	2, 4	None	1, 4	None
		P. T.	1 – 7, 9, 10, 12 – 15	1, 2, 4, 6, 10, 12 – 15	1, 4, 6, 7, [8], 10, 12 – 15	None	[8. A proton gradient is formed from the lumen to the stroma, which protons move down] 12. (NADPH ₂ and ATP are also products because they have been formed, even though they are used later in Stage 2 of the light-dependent reaction 13. (NADPH ₂ is high energy) as it has a positive charge
		D.P.T.	1, 4, 6, 9, 11, 12, 14, 15	1, 4, 6, 9, 11, 14, 15	1, 4, 6, 14, 15	12	8. A concentration gradient is formed so the electrons move from the lamellae into the stroma 10. The movement of protons and electrons being oxidised and reduced makes HADH + H ⁺ 13. All molecules are high energy molecules

Table 7.4 Results on tasks for high scoring pairs

PE *Photosynthesis Explorer*
CE *Cells and Energy*

7.3.5 Analysis and discussion

The most obvious feature derived from of results for the PE1 pair was the limited correlation between choice and statements at the start and the much greater correlation in the post-test stages, with links between correct choices and goal concept statements.

At the pre-test stage, there were greater confidence ratings about the responses than statements warranted. P1 delivered ten correct responses but statements on all of them failed either to supply sufficient explanation commensurate with the confidence rating or demonstrated misconceptions. Five were awarded high confidence values, though with incomplete written support. Thus in Task 6, for example, the statement that 'solar energy does not have electrons' was correct, but it did not supply the important detail that electrons were derived from water. Three misconceptions were evident, one of which on Task 8 is discussed in the discussion of misconceptions at the end of this section.

P2 was less confident about the responses made than P1. Six tasks were targeted correctly and on only two of them (11 and 13) were sufficient explanations provided that could justify the confidence awarded. On no other task did the descriptions measure up to the target responses. Three misconceptions were evident at this stage as noted in the results section and, two of them, on Tasks 14 and 15, 'the oxygen is released and the carbon which stays must be used and therefore carbohydrates are made' and 'the

equation cannot balance if it [oxygen] comes from water as water has merely O whereas the oxygen is O₂' are discussed at the end of this section.

At the post-test stage, P1 had become not only more confident about correct responses, but also appeared to be more polarised about the incorrect ones also. Ten correct choices were realised and there was a correlation between the descriptions and the confidence of response to most tasks. In nine of them, there was a match between a correct response and a partial or complete description in explaining why, as well as a link between three incorrect choices and the accompanying description. At the cognitive level, eight tasks qualified and four of them (6, 11, 14 and 15) were linked to a sound description.

For P2, there was a stronger link between the choice of response together with the confidence rating and the descriptions than for P1. There was an almost complete match between the assignment choice and the description. Thirteen correct choices (eleven highly confident) were made, eight of which held sound descriptions and the other five incomplete ones. Two choices were incorrect on Tasks 5 and 6 and misconceived comments on Task 6 were certainly anomalies since in general it was high scoring. The statement that 'the electron is needed in the light-dependent part of the chloroplast and splits water, releasing the oxygen' was wrong.

At the delayed post-test stage, P1 targeted fourteen tasks correctly all of which (except Tasks 5 and 7) were accompanied by partially or completely

correct comment. On chloroplast structure, greater consistency of choice and comment was evident than at the post-test stage, particularly in respect of the distribution of chlorophyll and of its location in two light harvesting units, though descriptions were incomplete. Those tasks that tackled topics covered in the interactive part of the program were awarded high cognitive scores except for Tasks 7, 9 (correct but low confidence) and 8 (incorrect).

P2 targeted thirteen tasks correctly, eleven at a highly confident level, nine of which showed partial or complete understanding. Unlike the post-test stage, goal conceptions were not met partially or fully on any aspect of chloroplast structure, but the interactive topics addressed on Tasks 6 and 8 to 15 delivered sound participant response – with very high confident scores and relevant comment.

The high initial scores of this pair did not suggest an understanding of the light-dependent reaction. What therefore did the trends in the post-tests suggest as to the participants' grasp of the topic as a result of using the *Photosynthesis Explorer* program?

They suggested that P1 held a sound understanding of the chloroplast at the post-test stage and of almost all of the topics covered in the interactive parts of the program. Although there was an incomplete correlation between target choices and written comment, there was a close one. It was the exception at the post-test stages to find a correct answer with an inadequate description and vice versa. At the pre-test stage this correlation was not so marked and

there was perhaps in the case of P1 the tendency to extract meaning from one of the statements without relating it to the light-dependent reaction in order to target the correct response. For example, in Tasks 12 the statement that 'anything made by a reaction is a product' is correct, but it did not merit a high confidence rating, since the task itself related to the actual products, NADPH, ATP and O₂. These data also suggested that P2 held a sound understanding of the chloroplast at this stage and of almost all of the topics covered in the interactive parts of the program.

At both post-test stages considerable improvements in their understanding were suggested by the results. Participants who responded correctly to Tasks 1, 2, 4, 6, 8 to 15 could be considered as possessing an understanding of the light-dependent reaction overall (see previous Chapter (p.233). Critically if the choices were very confidently made at the metacognitive (>60%) level and supported by descriptive material, then this evidence would strongly suggest an overarching understanding of the process.

In the case of P2, there was convincing evidence that at the post-test stage this was the case. Only Task 6 produced an anomalous and misconceived response. At the delayed post-test stage, Tasks 6 and 8 to 15 provided evidence for sound understanding. However, Tasks 1, 2 and 4 did not. Therefore, this participant's work with the *Photosynthesis Explorer* program seemed to generate immediately after its use a sound grasp of the light-dependent reaction in almost all aspects, but after a time interval this was retained only for the interactive aspects, which included detailed events from

light harvesting to the generation of ATP and NADPH as well as an overview of the whole process. This participant was less sure about the structural features of the chloroplast.

P1 produced less convincing data that this program produced an overall understanding at the post-test stage than P2, though more at the delayed post-test stage. The weakness at the post-test stage as well as the greatest mismatch between confidence rating and written comment came in the chloroplast structure and design tasks that were not part of the interactive part of the program. On Tasks 6 and 8 to 15 on the other hand (the interactive parts) there was a consistency of sound comment and correct confident choice on most tasks except on Tasks 8, 10 and 12. Whilst Task 8 was difficult overall, this participant, though opting for the wrong target in both tests, did produce sound comment. The choice made on Task 12 at the post-test stage was possibly an error, since the comment had relevance and was followed by a correct choice, as well as comment in the delayed post-test. On Task 10, at the post-test stage there was a possible misconception about reduced co-enzyme. With these reservations, this participant was able to demonstrate, within the interactive parts of the program a sound understanding of the light-dependent reaction.

There were few misconceptions overall. For both participants there were a few misconceived ideas at the start, though most of them were unlikely to influence an understanding of any concepts linked to the light-dependent reaction. The only two that were likely to affect conceptual development

related to the above phenomenon were on Task 8 for P1 where there was incorrect knowledge about the link between pH and proton concentration and for P2 on 14 and 15 where carbon dioxide was considered to be the source of oxygen. In this case, the program appeared to be effective in removing this misconception since, in both post-tests, responses suggested complete confidence both in choice and written statements as to the actual source of oxygen. For P1, where knowledge about pH and proton movement was required to target the correct choice on Task 8, evidence suggested that this member of the pair was unsure about the response, since the target choice was wrong in both post-tests, but comments were remarkably sound.

For P2 the program possibly caused misconceptions related to the thylakoid model presented in the program, since this member of the pair noted that 'the electron is needed in the light-dependent part of the chloroplast and splits the water, releasing oxygen' and '[the two photosystems are in the thylakoid] and NADPH is passed from here to the stroma', both of which comments were incorrect.

The most obvious features derived from the results of the CE4 pair were limited correlations of scores and descriptions at the start and much more in the post-test stages, though most particularly at the post-test stage.

At the pre-test stage, for both participants, there was a mismatch between the confidence scores and descriptions, with high confidence ratings linked to inadequate descriptions, particularly for C7. Both members achieved an

unexpectedly high number of correct choices – nine in each case, though certainly not always on the same task. C7 was much more liberal in awarding high confidence ratings, whether or not correct choices were realised. For both participants, it was only on certain chloroplast topics, Tasks 1, 2 and 4, which were of past experience, where written comments did for the most part correlate with choices. On the remaining tasks (5-15) correct choices were not generally supported by adequate comment. For example, C7 awarded a high confidence rating on Task 6 with the comment 'just a hunch' whilst C8 awarded correct choices to several tasks that received the comment 'unsure went with instinct'.

At the post-test stage, C7 was even more confident about many correct responses. Twelve correct choices were delivered and there was a positive correlation between the descriptions and the confidence of response to all of them (seven goal concept descriptions and five partial ones). C8 at the post-test stage delivered thirteen correct choices, nine of which were at a highly confident level. In general, there was close correlation between confidence levels and descriptions.

At the delayed post-test stage, C7 realised one more very confident correct choice (thirteen) than immediately after the program's use, though written comments did not correlate at all well with these highly confident ratings. Many were insufficiently specific, as on Tasks 1, 2, 4, 7, 11 and possibly 12, 13 and 15 as well. Others were only described as vague memories: Task 3, 'I just think maybe', Task 6, 'I remember that bit' and Task 14, 'I just remember

this, too'. C8 produced only eight correct responses at the delayed post-test stage (one less than at the pre-test stage, all of them at a metacognitive level and five of them supported by sound written comment – Tasks 1, 4, 6, 14 and 15, whilst one, Task 12, gained some support. There was a general correlation between both a correct or wrong choice and written comment. So that on Tasks 2, 3, 5, 7, 8, 10 and 13 a wrong choice was accompanied by a general comment that revealed nothing specific about the ideas tested on the tasks. In only two instances, on Tasks 9 and 11, was a mismatch revealed between confidence measures and comment.

These data, at the pre-test stage, suggested that C7 held a sound knowledge and understanding of chloroplast structure, whereas C8 was less sure. Responses to Task 3, however, suggested that this pair held no knowledge at all about light harvesting units – nor were they expected to, since this topic is not covered in first year of sixth form work. In addition, except for knowledge of chloroplast structure, this pair knew almost nothing about the light-dependent reaction at the outset. What therefore did the trends in the post-tests suggest about the grasp of the topic as a result of using the *Cells and Energy* program?

Based on the first four tasks, the immediate post-test data for C7 suggested an adequate knowledge of chloroplast structure, which was little changed from the pre-test stage. The tasks related to light energy, electrons, protons and their movement and the synthesis of reduced NADP and ATP (Tasks 6, 7, 8, 9 and 10) produced mixed responses, with the wrong choice made to Tasks 8

and to 10. These wrong choices carried either no comment or a meaningless one. On the other hand, other responses were fully and correctly explained. Reference to the perceived difficulty of Task 8 has been made in Chapter 6: it appeared to be low scoring generally. In the interactive tasks – Tasks 6 to 15 – this participant appeared to possess a sound understanding of the topics tested by these tasks. The only exceptions were related to the material in Tasks 8 and 10. At the delayed post-test stage the numerical responses suggested a sound understanding, other than for the ideas tested in Tasks 3 and 10, which was generally consistent with the post-test data, though descriptive material rarely reached the level of the goal concept.

C8 appeared to hold sound understanding of the vast majority of topics tested in the tasks at the post-test stage – immediately after the program's use. Nevertheless there was some doubt concerning the structure of chloroplasts, since two of the written responses (on Tasks 2 and 3) were not supportive of the correct choices. At the delayed post-test stage, knowledge and understanding appeared to be less certain than at the post-test stage, since there was one less correct choice at a metacognitive level and many more overall, as well as a reduced number of goal concept comments.

Using Tasks 1, 2, 4, 6 and 8-15 once again, what is the evidence that either of these participants understood the light-dependent reaction at the post-test stages?

First, at the post-test stage, most choices were made at a very confident level (even more than the high confident levels expressed by C7 at the pre-test stage) and, second, descriptive comments explained, in biological terms, reasons for these choices. There was an especially sound description to one overview task, Task 14 by C7, '[oxidation of] water releases oxygen and also protons and electrons, both of which are used in the synthesis of NADPH + H⁺ and ATP'. The only descriptions that missed salient points appeared on Task 3 for both participants, on Tasks 8 and 10 for C7 and on Tasks 2, 5, 9 and 11 for C8. As already noted Tasks 3 and 5 were not considered to be essential for an overall understanding of the process. Task 8 was difficult for the whole cohort, which left perhaps only specific weaknesses on Tasks 2 (C8) (location of the light-dependent reaction), 9 (C8) (ATP synthesis), 10 (C7) (synthesis of NADPH) and 11 (C8) (the interdependence of the light-dependent and independent reactions). Nevertheless these results suggested that most of the evidence supported the view that both participants held an overall understanding of the process at the post-test stage.

At the delayed post-test stage, the confidence rating evidence suggested that C7 still possessed sound understanding. However, this was probably insufficient for long-term gain as a result of the use of the *Cells and Energy* program for two principle reasons. First, this participant assigned high confidence ratings at the start without general justification and second at this stage most comments once again failed to explain the reasons for the high confidence values. Many comments were restricted to, 'I just remember this...'. For 8C there was perhaps more evidence of long-term gain, both by

the higher confidence ratings on many tasks than at the pre-test stage and by better descriptions on some tasks than the other member of the pair. However, the evidence was incomplete since, although data suggested some aspects of chloroplast structure were better understood than at the pre-test stage, the interactive part of the program had not sustained the grasp of the topics for this participant evident at the post-test stage. Indeed on these interactive elements only results on Tasks 6, 14 and 15 suggested secure evidence of long-term gain. These were on the initial impact of light energy on the chlorophyll molecule and on the overview topics, which included the source of oxygen and the overall equation of photosynthesis. On the in-between detail concerned with ATP and NADPH synthesis the evidence was not secure. There were correct choices, but also incorrect ones at very high confidence levels.

Overall for these participants, the program had an immediate effect on their understanding of the light-dependent reaction. However, this may not have been sustained for a longer period after its use.

Misconceptions were not revealed in the pre-test for either participant or in the post-tests for C7. Nevertheless there were a number revealed in the post-tests for the other participant – three at each of the post-test stages, one of which, on Task 8, appeared in a different form at the two stages. Most of these, except that on Task 13 in the delayed post-test, concerned charged molecules, protons and their movement. In response to Task 8, proton movement was just possibly described in the wrong direction at the post-test

stage and, at the later stage, changes were ascribed to electrons changing compartments.

7.3.6 Results for a mixed scoring pairs

The summarised results from the *Photosynthesis Explorer* pair (PE2, with Participant P3 being the low scoring member) are displayed in Table 7.5. Both participants provided explanatory information as to the reasons for the choices made at every stage and on the great majority of tasks. P4 especially delivered descriptive comments in very great detail.

Results for CE5 (the equivalent *Cells and Energy* pair) are also shown on the same table. The most obvious feature of these was the difference between the extent and number of comments expressed by the participants. Participant C9 (the low scoring member of the pair) expressed no reasons for the choices made at the pre-test stage and on only two tasks at the delayed post-test stage. More comments were forthcoming in the post-test, but they were brief and only provided for ten tasks. Participant C10 on the other hand produced comprehensive comment at the pre- and post-test stages on every task, though rather less in the delayed post-test, where only ten of them were embellished with reasons.

Program	Participant	Test stage	Tasks				Misconceptions
			Correct responses	Highly confident correct responses	Goal concept	Partial goal concept	
P E	P3 (L)	Pre-test	6, 9, 13	None	None	13	5. Because wavelength is longer, more room for energy
		P. T.	2, 4, 5, 6, 9, 11, 13, 14, 15	2, 6, 13, 14	2, 5, 6, 13, 14	9, 11	10. I just remembered NADH from the program – not sure 12. The ATP and NADPH are outputs instead of products
		D.P.T.	2, 4, 7, 9, 10, 12 – 15	2, 15	None	2	None
	P4 (H)	Pre-test	4, 5, 9, 12, 13	4, 5, 9, 12, 14	5, 13	4	8. Negative charges raise pH levels 14. Electrons are not lost in the reaction so B is incorrect, but carbon is released and used to build glucose
		P.T.	1 – 6, 8, 10 – 15	1 – 6, 8, 10 – 15	5, 6, 8, 11 – 15	1 – 4, 7, 9, 10	None
		D.P.T.	1, 2, 4, 5, 6, 8, 9, 11, 12, 14, 15	1, 2, 4, 5, 6, 8, 9, 11, 12, 14, 15	5, 6, 8, 11, 12, 14	1 – 4	13. "B" is the incorrect answer because "A2 suggests the oxygen is a chemical, this is untrue
C E	C9 (L)	Pre-test	4, 8, 9, 12, 14, 15	15	None	None	None
		P.T.	1, 3 – 6, 8 – 10, 12 – 15	1, 4 – 6, 9, 12 – 15	6, 10	None	None
		D.P.T.	1, 2, 6, 9, 12 – 15	1, 6	None	None	None
	C10 (H)	Pre-test	1 – 7, 9, 11, 13, 15	1 – 7, 9, 11, 13, 15	None	1, 2, 11, 13	14. This seems to make more sense as one of the essential elements in carbohydrates is carbon 15. The equation would still balance if the oxygen came partly from water. In the actual reaction there will be more water available anyway
		P.T.	1, 2, 4 – 7, 9 – 15	1, 2, 4 – 7, 9 – 15	4, 6, 8, 9, 11 – 14	1, 2, 7, 10, 15	3. Only one kind of light harvesting unit - chlorophyll
		D.P.T.	1, 2, 4 – 7, 9, 11 – 15	1, 2, 4 – 7, 9, 11 – 15	6, 8, 9, 11, 14, 15	1, 2, 13	None

Table 7.5 Results on tasks for mixed scoring pairs

7.3.7 Analysis and discussion

The most immediate features derived from the data for the *Photosynthesis Explorer* pair were the improvements in correct choices on the tasks for P3 (the low scoring member) at the post-test stage only and across both tests for P4.

At the pre-test stage, for both participants, there was an overall correlation between choice and commentary, though this linkage occurred between incorrect associations.

At the post-test stage, also for both participants, there was considerable evidence for linkage, particularly for P4, though now with right choices and relevant descriptions. P3 linked each of seven correct choices to an appropriate statement and to each incorrect choice an irrelevant or misconceived description. However, whilst the positive effect of the program was shown by the scientific terminology used in contrast to the general statements in the pre-test, grouping of responses was problematic and the ideas expressed occasionally demonstrated confusion.

In terms of the interactive tasks, P3 results were very mixed, though Task 6 (on the source of electrons), Task 13 (high energy molecules) and Task 14 (water splitting) gained high confidence ratings and secured goal concept comments. For this participant, though, the only aspect of the chloroplast structure topic that secured both confidence of correct choice and relevant descriptive comment was on Task 2 concerning the location of the light-dependent reaction. On Task 10, there was confusion about the difference between NADPH and NADH, leading to an incorrect choice and on Task 12 between outputs and products.

This pattern of correlation was even more evident for P4. Indeed, this member demonstrated a general link between thirteen highly confident correct choices and sound descriptive comment. In fact, each of these generated such a correlation and, of these, eight realised a goal concept. The only correctly targeted choices, where comment was less than complete, appeared on Tasks 1, 2, 3, 4 and 10. On the only two occasions where this participant registered the wrong choice (Tasks 7 and 9), descriptions were conceptually sound.

At the delayed post-test stage, P4 produced eleven very confident correct choices (two less than at the post-test stage) and continued to demonstrate a general association between them and sound descriptions, whereas P3 only gained two. For this participant also, many choices were so insecure as to merit confidence levels of zero. Only one description supported, to an extent, the correct choice on one task only, Task 2. The rest were of a very general kind and acknowledged guesswork.

At the start the pre-test evidence suggested that neither of them held much knowledge or understanding about chloroplast structure or about the light-dependent reaction, but what does the evidence suggest at the post-test stages?

At the post-test stage, for P3, there did not appear to be a pattern of understanding, though the positive effect of the program was evident in the language used, but the ideas expressed frequently suggested confusion. For

this participant, the results suggested that there was greater understanding of the light-dependent reaction in the post-test stages, though primarily in the immediate post-test stage as represented both by confidence measures and by written statements. Results suggested that some progress was made at the post-test stages on the development of an understanding of chloroplast structure (Tasks 1-4) using this program. This was primarily on the location of the light-dependent reaction. For P4, these changes were much more marked and sustained to the delayed post-test stage. These aspects were delivered incidentally, rather than as a result of any interactive activities available in the program itself.

For P3, if metacognitive levels of response are taken as a recognition of understanding of topics covered in Tasks 5-15, then at the post-test stage only two elements qualified – water splitting and the names of the two high energy molecules. Other aspects that held some understanding, such as ‘movement is needed by the protons’ [for ATP synthesis] and ‘...the light-dependent reaction can take place in the light and the dark’ suggested some recall from interactive activities, but hardly met the demands of the target responses on Tasks 9 and 11. Therefore whilst this participant had gained considerably after immediate use of the program, the changes could best be described ‘as a memory of specific bits of it’, so that even those choices that qualified at >60% were not conceptualised in terms of the light-dependent reaction overall. There was, therefore, limited evidence that this participant immediately after using this program developed an overall understanding of the light-dependent reaction as judged by responses to Tasks 1, 2, 4, 6 and 8

to 15. Long-term, the evidence was even more tenuous and was best summed up by the participant's comment to Task 15, 'I can vaguely remember so I hope it's right, but I definitely will understand when I do this again'.

For P4, there was sufficient evidence to support the view that understanding was gained and retained for the period of the investigation. In terms of Tasks 1, 2, 4, 6 and 8 to 15 there were detailed and relevant descriptions to every item in the post-test and only one wrong choice, on Task 9. At the delayed post-test stage, the only incorrect choices from this list appeared on Tasks 10 and 13.

Misconceptions were rarely evident in any of the descriptions. P3 suggested only one misconception at the outset about light energy, which was unlikely to materially affect an understanding of any aspect of the light-dependent reaction. P4 held two preconceived ideas, which were registered in response to Tasks 8 and 14. The first referred to electrons and pH, which was corrected as a result of the program's use and the second concerned the source of oxygen. However this was not very firmly held, since in the next task, Task 15, the source of oxygen was suggested to be water, 'so maybe oxygen does come from water'. In the following tests both Tasks 14 and 15 received the highest confidence rating and goal concept recognition. The only misconceptions that possibly arose from the program were related to the name of a product and confusion between the words outputs and products. P3 in the post-test considered NADH to be a product (output) rather than

NADPH on Task 10. On Task 12, the word output was used in the program, but in the test the word product. In a similar vein, P4 targeted Task 13 incorrectly in the delayed post-test, because oxygen was described as a chemical in the test task, rather than a molecule.

The most obvious features, derived from the results for the low scoring member of the *Cells and Energy* pair (C9), were the greater confidence in and number of correct responses at the post-test stage, which essentially disappeared at the delayed post-test stage. For C10 the prevailing trend was an increased number of goal concepts (rather than number and confidence of correct scores) expressed in the post-test stages, which peaked in the post-test.

For C9, no correlation was established between confidence measurement and descriptions not only at the pre-test stage (because there weren't any), but also at any of the post-test stages either because there were so few.

For C10 at the pre-test stage written material did not generally support confidence expressed in the eleven highly confident choices made. No overall association was established, though there was a close one between correct choices on Tasks 1 and 2 in relation to chloroplast structure. On other tasks, scientific knowledge, understanding and logical argument were employed that occasionally met with part of the target responses, but these never included information about the light-dependent reaction and occasionally, too, they were misconceived. On occasions this logic, realised the incorrect response. The following examples illustrate these points. On

Task 13, the fact that oxygen was not a high-energy molecule was acknowledged, but there was no description of the energy content of the other two compounds, which suggests that this was not known. A high confidence rating was not justified. On Task 14, the comment 'this [in reference to Choice A] seems more sense as one of the essential elements in carbohydrates is carbon' illustrated a misconception that carbon dioxide was the source of oxygen. On Task 8, the comments that 'protons or H^+ ions increase acidity lowering pH. Loss of H^+ ions should therefore increase lowering acidity' was well argued, but failed to explain these events in terms of the changes between the stroma and thylakoid. Therefore, the choice selected was incorrect. The only topic that held a measure of consistency was that covering chloroplast structure. Here all four tasks recorded correct choices, three of which (Tasks 1, 2 and 4) were topics of past experience. On Task 3, logic was employed to derive the correct choice as to the reasons for chloroplasts carrying two types of light harvesting units. The statement that 'It is sensible to suggest that the two different units working together can double the amount of work done' did not provide any detail as to the operation of the two light harvesting units.

At the next stage, for C9, numerical data demonstrated highly confident choices on nine of the twelve correct responses (an increase of eight and six respectively). There was, however, no correlation between these and the comments made, which were either absent or very limited except on Tasks 6 and 15. Not only was confirmatory evidence of the choices absent or incomplete in many cases, it also lacked scientific language. This point is

illustrated by the response to Task 1, 'it [chlorophyll] in the picture was in blobs', which hardly represented a scientific description.

For C10, on the other hand, although the number of highly confident responses only increased from eleven to thirteen, evidence of the program's effects were expressed in many ways. First, compared to the pre-test, confidence ratings were increased to the maximum level possible in three of the correctly targeted choices and in two of the four incorrect ones; second, the positive association between confidence ratings and descriptions, which referred to detail of the light-dependent reaction; third, in failure of descriptions on Tasks 5 and 7 to advance further than those in the pre-test (since the material tested was not included in this program) and fourth, on Tasks 3, to express a misconception inherent in the program itself. The most obvious anomalous result was the mismatch between the choice on Task 8 (which was very confidently wrong) and the description, which realised the goal concept linked to the role of energised electrons – 'the energy the electrons lose is used to move the protons into the granal lumen' – in proton movement. The reason for this is best described here, rather than in the section on this participant's knowledge and understanding, since it is an anomalous result. This was not caused by lack of understanding of the meaning of pH since this was clearly expressed in the pre-test. The answer possibly lay in a misreading of the opening statement in the Task itself, 'electron transfer.....provides energy for the movement of protons across the lamellae into the stroma'. In addition, a possible anomaly lay in the description associated with Task 10. The explanation that 'the electrons move along

[within the thylakoid membrane] and lose energy to the protons. This could then give them enough energy to react with other chemicals' was an attempt to explain the processes whereby reduced co-enzyme was synthesised. This was possibly flawed.

For C9 at the delayed post stage it was not possible to locate correlations between choices and comments, since this participant only offered reasons on two occasions. However, another possible avenue, in this case, was to consider consistency of results across the tests. Only two tasks secured highly confident ratings (1 and 6) – a reduction of seven – that were very nearly consistent with those at the post-test stage, but most other data were not disposed to this consistency. The exceptions to this occurred on Tasks 12 to 15, where correct choices appeared, though not at a highly confident level.

For C10 there were fewer correct choices than at the post-test stage, down from thirteen to twelve, which was a minimal change, but the descriptions and explanations associated with them were omitted on five tasks and much less informative on most of the others.

What knowledge and understanding are suggested from this analysis? It was probable that C9 held only very limited biological grasp of chloroplast structure and function and the light-dependent reaction before the program's use. For C10 such a suggestion was more problematic. However as developed in the analysis, high confidence ratings for the majority of choices were not supported by statements that accompanied the most of them, except for

Tasks 1 and 2 at that stage. What did the trends in the post-tests suggest as to participants' understanding as a result of using the *Cells and Energy* program?

In the post-test, for C9, comments were either absent or vague, except in two cases (Tasks 6 and 15), on topics regarded as essential for an understanding of the light-dependent reaction. Even though ten out of the twelve tasks deemed to demonstrate an understanding of the light-dependent reaction were correctly targeted, it was not possible to consider with any confidence that this participant held an understanding of the process. However, there was support for the view that these numerical values did represent the effect of the program on understanding, since in response to Tasks 3 and 7 particularly, there was zero confidence in the right (Task 3) or wrong (Task 7) choice and the comments that 'I have no idea' (Task 3) and 'I don't know what the Hill reaction is' (Task 7) were really appropriate since the program could not assist on these tasks.

It was possible, therefore, to hold one of two alternative views. Either this participant understood many events of the light-dependent reaction identified from the confidence of choice, or that very little understanding was demonstrated since the only support for the numerical data was that 'electrons come from water' (Task 6) and 'the oxygen comes from water splitting (Task 15). Further evidence through audio, video and hypercam recording was sought for the most appropriate conclusion.

For C10, in contrast to C9, at the post-test stage there was abundant written evidence of understanding suggested by numerical data. At this stage, therefore, this participant's results suggested a sound understanding of the principle concepts of the light-dependent reaction, as addressed in Tasks 1, 2, 4, 6 and 8 to 15. The responses to tasks, which were dependent on interactions within the program (6 and 8 to 15), were all improved in both consistency and confidence of choice as well as the quality of description associated with each one.

In the delayed post-test, the information provided by C9 about the long-term effect of the program's use was even more problematic than at the post-test stage. There was, however, the possibility that the conceptual ideas tested in Tasks 1, 6 and 15 were reasonably established long-term as well as those in Tasks 12, 13 and 14, too, though less so. These were about the distribution of chlorophyll in chloroplasts, water splitting and the nature of the products of the light-dependent reaction.

For C10, the delayed post-test data suggested a reduced level of knowledge and understanding when compared to the results in the post-test, except possibly on chloroplast structure topics. In the interactive sections, residual knowledge and understanding about the initial events and about the changes to the overall equation of photosynthesis were maintained (Tasks 6, 14 and 15). However, little descriptive evidence appeared elsewhere, other than on Task 9, which concerned the role of protons in ATP synthesis. On Tasks, 10 and 12 none appeared and on Task 13, the excellent description in the post-

test that 'NADPH₂ and ATP are high energy molecules' declined to that of the pre-test that 'oxygen is not a high energy molecule'.

Results suggested that this participant held essential knowledge of chloroplast structure (with one possible misconception carried over from the post-test stage about the number of types of light harvesting units). In addition, ideas about the water splitting and its effect on the overall equation of photosynthesis appeared to be firmly entrenched. However, the participant's appreciation of the intermediate events appeared not to be secure long term.

C9 did not deliver any misconceptions. C10 held one preconceived notion as to the source of oxygen. This was revealed on Tasks 14 and 15 through comments such as 'This [carbon dioxide] seems more sense as one of the essential elements in carbohydrates is carbon'. Nevertheless the use of the program removed this misconception as was revealed in the post-tests. At the post-test stages, Task 3 revealed a misconception associated with the number of types light harvesting units. This participant thought that there was only one, which was shown in the model of the thylakoid structure within the program.

7.3.8 Results for low scoring pairs

The most obvious feature of the raw data for Participants P5 and P6 was the lack of descriptive comment at the delayed post-test stage, whilst for Participants C11 and C12 there was limited descriptive comment overall. Whilst participants provided commentaries at every stage and in almost every

cell, they were very brief. A summary table of the results is shown in Table 7.6.

Program	Participant	Test stage	Tasks				Misconceptions
			Correct responses	Highly confident correct responses	Goal concept	Partial goal concept	
P E	P5	Pre-test	2, 4, 6, 12	2, 12	None	4	1. Chloroplasts can move to the surface 5. I think the longer wavelengths carry more energy 12. ATP is in the equation [another product].
		P. T.	2, 4, 6, 9, 10, 12, 14, 15	2, 4, 6, 9, 10, 12, 14, 15	2, 10, 12,	6, 8, 9, 11, 14	5. Red light is absorbed more by leaves
		D.P.T.	1, 4, 5, 6, 9, 11, 14, 15	1, 4, 5, 6, 9, 11, 14, 15	None	None	None
	P	Pre-test	1, 2, 4, 6, 8, 9, 11, 12, 13	13	6	2, 9, 13	4. Pigments aren't always found on the outside of chloroplasts 5. You can feel infrared radiation much more strongly than UV radiation 14. Oxygen is not needed but the carbon is the oxygen is released 15. H ₁₂ cannot be correct unless the oxygen comes from the carbon dioxide
		P.T.	2, 4, 5, 6, 9, 10, 12, 14, 15	2, 4, 5, 6, 9, 12, 14, 15	2, 5, 6, 9, 10, 14, 15	4, 8, 11, 12	3. The thylakoid and stroma are joined 13. Oxygen is a high-energy molecule
		D.P.T.	1, 2, 4, 6, 9, 10, 11, 13, 15	1, 2, 9, 11, 15	None	None	None
C E	C11	Pre-test	4, 7, 9, 10, 11	4, 9	None	None	None
		P.T.	1-4, 6, 7, 11-15	1-4, 6, 12-15	9, 13	1, 4	None
		D.P.T.	1, 4, 6, 9, 12, 13	1, 4, 6, 12	None	9, 11	14. Plants can absorb more carbon dioxide than water
	C12	Pre-test	1, 5-9, 11, 14	1, 5	None	None	None
		P.T.	1-4, 6, 9, 12-15	1, 2, 6, 9, 12-15	14, 15	1-4, 13	11. Two processes are independent and LIR occurs in the dark
		D.P.T.	1, 2, 9, 10, 12, 13	1	None	9	11. There were two phases on the computer that we went through 13. They [referring to the products of the light-dependent reaction] need to be high-energy to produce ATP 15. It [oxygen] must come from carbon dioxide and water

Table 7.6 Results on tasks for low scoring pairs

7.3.9 Analysis and discussion

There were three common features derived from the results of this pair (PE3): first, the increased number of correct responses in both post-tests compared with the pre-test; second, the irregularity of choices between the post- and delayed post-test stage and third, the increase in number of goal concepts achieved in the post-test.

At the start, P5 generated four correct choices (2, 4, 6 and 12) - all, except 2 and 12, at a confidence level of zero. The uncertainty on seven incorrect choices was expressed both by the low confidence rating (<20%) and possibly also by lack of any comment whatsoever. Generally where higher confidences (>40%) (six tasks) to correct or incorrect choices were delivered brief explanations accompanied them. The remaining incorrect choices (1, 3, 5 and 11) were in two cases (1 and 5) explained by misconceptions and in the other two with little (3 – 'not sure') or nothing at all (Task 11). These data provided no support for a correlation between correct choices and descriptions.

P6 also demonstrated little correlation between correct choices and descriptions at the pre-test stage either, though more correct ones were delivered (nine as opposed to only four). Amongst these, confidence levels were low (<40%), except in Task 13 where the higher value was supported by a relevant comment. In other cases, the target response was not met at all, in part only, or intermixed with a misconception, such as in Task 6, 'water provides the oxygen and electron for oxidation'.

At the post-test stage, P5 delivered eight correct choices (up from four) -all at high confidence ratings; the remainder also received equivalent values in all cases (except one). Six correct ones contained relevant descriptions and of the seven that were wrong, two carried no descriptive comments and the rest were either not related to the target response (two), carried some relevance (two) or were misconceived (one). There was therefore evidence of a correlation between choice and comment. On Tasks 1-4, this participant used the terms thylakoids and stroma, though not in the context of the goal concept, other than in Task 2, where the description 'the light-dependent reaction occurs in the thylakoids' was correct. Other correct choices and accompanying relevant comment appeared in response to Tasks 6, 9, 10, 12, 14 and 15 (as well as one on an incorrect choice Task 8). Nevertheless they were very brief, lacked explanatory detail and were selective to such an extent that they were often little more than an extract from a phrase provided in the task. For example, in Task 9, the statement 'ATP synthase is an enzyme' hardly explained the mechanism of ATP synthesis, though it did provide a reason for the choice as did the response in Task 10, 'because PS1 and PS2 were in the membrane and $\text{NADPH}_2 = \text{NADPH} + \text{H}^+$ '.

For P6, the same number of correct choices (nine) was delivered as in the pre-test (though not always on the same task). Eight were expressed very confidently and containing relevant comment. Incorrect choices were accompanied by irrelevant comment (two) or by a misconception (two). The description 'the light-dependent reaction only occurs in the thylakoid' went

beyond anything contained in either of the alternatives statements in the task itself. Nevertheless on Task 4, the statement, 'the light harvesting units join the stroma and thylakoid, which are within the inner membrane' was both ambiguous and insecure. On Tasks 5 to 15, six (5, 6, 9, 12, 14 and 15) were correct at the metacognitive level, whereas Task 10 was expressed less confidently. In general, descriptions were much more meaningful than those by the other participant, whose comments were little more than mere recognition of words and phrases. Thus on Task 9, the statement 'ATP synthase is activated by the movement of protons' demonstrated an understanding of processes rather than as in P5 recognition of a name 'ATP synthase is an enzyme'. Tasks that proved generally difficult, Tasks 3, 7, 8, were targeted incorrectly and Task 13 was, too, by considering that 'oxygen is a high energy molecule' in contrast to the statement in the pre-test.

At the delayed post-test stage, P5 maintained eight correct choices, though only five of them (4, 6, 9, 14 and 15) were consistent with those at the post-test stage. There was, as has already been stated, no comment on any task at all, so that correlation between choice and comment could not be established.

This lack of comment featured in P6's test, too. Nine correct choices were delivered (up one from the post-test), but only five were registered as highly confident and of these only three (2, 9 and 15) reached the level achieved in the post-test. Only three other correct choices were consistent with those at

the post-test stage (4, 6 and 10) and they each realised the same 40% confidence level, which was a reduction from the previous stage.

Since there were no written responses, further comments on any other patterns at this delayed post-test stage alone have little value, but an attempt is made below to link choices with those at the post-test stage in order to reveal trends. On Task 1 to 4, for P5, two were correct, though only one (Task 4) in common with the post-test. On the other tasks, four correct choices – all highly confident – were in common with those at the post-test, which were Task 6 on the source of electrons, 9 on ATP synthesis and 14 and 15 on overview matters. P6, as for P5, produced no written comment. For this participant, two correct choices were found on Tasks 1 to 4, but only one (Task 2) on the location of the light-dependent reaction was common at the same high confidence level with the post-test rating. Only two other tasks, Tasks 9 and 15 (on ATP synthesis and the overview reaction) showed this level of consistency, whilst three others on Tasks 4, 6 and 10 (on light harvesting, water splitting and synthesis of reduced co-enzyme) showed a reduction in confidence.

What do these trends and patterns reveal about the knowledge and understanding of the light-dependent reaction, both before and after the use of the *Photosynthesis Explorer* program?

At the outset, results suggested that neither of these participants held much understanding about those aspects of photosynthesis tested by these tasks,

even though P6 attained nine correct responses – only one at a highly confident level. Whilst every choice merited a written comment, there was limited support for the correct choices realised and the highly confident wrong ones were supported by misconceptions. Neither participant appeared to possess much knowledge of chloroplast structure and design either.

For P5, whilst positive effects on this participant's knowledge of chloroplast structures were evident in the confidence values secured and descriptions on Tasks 2 and 4 these were possibly counteracted by the much-reduced confidences in the other two tasks on chloroplast design. Similar suggestions could also be made for P6. Indeed, both participants were aware of the thylakoids as locations for the light-dependent reactions, whereas neither of them was before. However, detailed descriptions of chloroplast structure and overall design as well as the location of the light-harvesting units were not secure. Those tasks where topics were included in the interactive part of this program (all the remaining ones) received mixed responses, like those on chloroplast structure.

For P5, the post-test results suggested insecurity in overall knowledge, in addition to the weaknesses on chloroplast structure. Only Tasks 6, 9, 10, 14 and 15 in the interactive parts of the program produced confidence values and appropriate comment. However, as noted earlier some of these comments (on Tasks 9 and 10) did not identify processes but rather recognition of names. The most likely view is that at this stage knowledge and understanding was

restricted to the site of the light-dependent reaction (Task 2) and the water splitting process (Tasks 6, 14 and 15).

For P6 data suggested that overall a more comprehensive body of understanding was secured. In this case, there was an appreciation of the water splitting process releasing oxygen and the effects on the overall equation (Tasks 6, 14 and 15), the processes involved in the synthesis of ATP and reduced co-enzyme (Tasks 9 and 10). The comment on Task 12 'because a substrate is used does not mean it is not a product' was sufficient to judge that ATP, reduced co-enzyme and oxygen were all products of the light-dependent reaction. Nevertheless the reasons for the links between the light-dependent reaction and the light independent reaction were insecure (Task 11), as was the energy of these products, with oxygen being quoted as a high-energy molecule.

What does this discussion suggest about this Participant's overall understanding of the light-dependent reaction? When the responses to Tasks 1, 2, 4, 6 and 8 to 15 are considered, this participant responded correctly to Tasks 2, 4, 6, 9, 10 12, 14 and 15 with suitable descriptive comments, which provided support for the view that an overall understanding had been achieved. There were some omissions that cast doubt on this view, most notably the role of light energy in this process, the role of protons (reducing power) and electrons in the generation of high energy compounds and their relationship to the light-dependent reaction, as well as the insecurity expressed in chloroplast structure.

At the delayed post-test stage what suggestions can be put forward as to participants' understanding of the light-dependent reaction. If the suggestions made from the post-test data for participants are valid, what can be derived from the limited data available at the delayed post-test stage?

If Tasks 1, 2, 4, 6 and 8 to 15 are used once more for this purpose, then P5 at the delayed post-test stage attained correct choices at a highly confident level on six of them, Tasks 1, 4, 6, 9, 11, 14 and 15, but what actual confidence could be expressed in them? Since erratic events were found on Tasks 1 and 11, then only on Tasks 4, 6, 9, 14 and 15 could some legitimacy be expressed in the data. However, with the lack of clarity in the written response to Task 4, 'stroma and thylakoid are inside chloroplasts' at the post-test stage, any residual understanding of chloroplast structure was most doubtful. This, therefore, left a long-term understanding of ATP synthesis and the water splitting process, which is not dissimilar to that at the post-test stage.

P6 gained nine correct choices at this stage on Tasks 1, 2, 4, 6, 9, 10, 11, 13 and 15, with six (2, 4, 6, 9, 10 and 15) in common with the post-test, though only 1, 2, 9, 11 and 15 reached a highly confident level. If erratic events (where incorrect choices were made in the post-test) are removed, (Tasks 1, 11 and [13]), then only three features were confidently held – the association of the light-dependent reaction with the thylakoids (Task 2), the synthesis of ATP (Task 9) and possibly the water splitting process (Task 15). If lower confidence values are included, then responses to Tasks 2, 4, 6, 9, 10 and 15 (Tasks 1, 11 and 13 removed) suggested that this participant possessed

rather more knowledge and understanding at this stage. First, on chloroplasts - that they contained thylakoids, with light harvesting units attached to them - second, on the water splitting process and, finally on the synthesis of ATP and reduced co-enzyme. Whatever level is applied long-term understanding of the light-dependent reaction was restricted.

At the start neither of these participants demonstrated many misconceptions. The only one judged as having a potential effect on learning about photosynthesis was the source of oxygen, suggested by Participant 6 as carbon dioxide. Nevertheless the results on Tasks 14 and 15 in the post-test suggested that the program was effective in removing this. Even so, comments about chloroplast structure, such as 'chloroplasts can move to the surface' (P5) and 'pigments aren't only found on the outside of chloroplasts' suggested important deficiencies in prior knowledge (P6). At the post-test stage, this defective conceptual grasp was confirmed by the rather naïve comment that 'the thylakoid and stroma are joined'.

The most obvious features derived from the results of this pair (CE6) were the limited comments provided by them in response to each task, the increase in the number and confidence of choices made in the post-test and the almost total disappearance of this effect long-term. These restricted comments limited opportunities to explore their understanding or lack of it. Nevertheless the following comments are relevant.

At the pre-test stage, C11 demonstrated no correlation between choices and descriptions. Most choices (ten), whether correct or not, were made at a highly confident level, only four of which were credited with a reason, other than a guess. C12 restricted such confident choices to five, but in every response to all tasks guesswork was acknowledged.

At the post-test stage, the number of correct responses increased in both cases to eleven (from five) for C11 and to ten (from eight) for C12, with a degree of correlation between choices and reason. For example, C12 acknowledged seven correct choices with a more extensive reason other than 'learnt from CD'. However, for C11 the vast majority of comments showed no link to the correct choices made, other than a reference to the program. Nevertheless on Tasks 1-4 (the chloroplast structure tasks) both participants realised correct responses and generally relevant descriptions, especially for C12.

C11 gained seven correct choices on the remaining eleven tasks and all of them, except 7 and 11, at a highly confident level, though only one, Task 13 carried a description that conformed to the goal concept 'only NADPH_2 and ATP are high energy molecules'.

C12 in some respects carried a similar profile to C11 with five common correctly accomplished tasks on the remaining eleven (6, 12, 13, 14 and 15).

At the delayed post-test stage, there was little if any correlation between correct responses and comment for either participant. The number of correct responses overall declined by five (from eleven to six) for C11 and by four (from ten to six) for C12, with very little overlap between them.

What do these trends and patterns reveal about the knowledge and understanding of the light-dependent reaction, both before and after the use of the *Photosynthesis Explorer* program?

At the start, the data suggested that neither of these participants knew much about the structure of chloroplasts or about the light-dependent reaction. Nevertheless the program appeared to have a marked effect on participants' ability to target choices correctly at the post-test stage. For both participants, these effects were most marked on the chloroplast tasks (1-4) and most notably on Tasks 12, 13, 14 and 15, but also on Task 6 for both participants and Task 9 for C12 only. Nevertheless the comment made in association with the choice in Task 9 by this same participant together with the correct choice and relevant comment delivered in the delayed post-test suggested that this participant may have possessed an understanding of the mechanism of ATP synthesis. Thus there was a close consistency between these participants as to which sections of the program enabled them to realise correct choices. Tasks 5 and 7 were not accessible using this program and choices and comments reflected this: C11 stated 'didn't learn from the program' and 'no idea' on Tasks 5 and 7 respectively, whereas C12 expressed both as 'guesses', the only responses that were solely acknowledged as such at this

stage. On the other hand, correct choices on Task 3 were anomalies, since the program did not provide them with any information about pairs of light harvesting units.

If the choices and comments in Tasks 1, 2, 4, 6 and 8 to 15 are used as a measure of understanding of the light-dependent reaction, what was the position of these two participants immediately after the program's use?

For C11, Tasks 1, 2, 4, 6, 12, 13, 14 and 15 received the correct choices at highly confident levels and C12 did so on Tasks 1, 2, 6, 9, 12, 13, 14 and 15. In addition, it was possible to suggest that both participants should have awarded this high level to Task 9 as well. These data suggested an understanding of chloroplast structure and design, the effect of light energy on a chlorophyll molecule, the processes involved in ATP synthesis, the products of the light-dependent reaction and their energy content, together with the light splitting process, the source of oxygen and its consequent effect on the overall equation. The missing bits were those that involved Tasks 8 (protons movement into the thylakoid lumen), Task 10 (the mechanism for the production of reduced co-enzyme) for both participants and Task 11 (the interdependence of the light-dependent and independent reactions) for C12. These data suggested an overall understanding though with a small number of missing elements at the post-test stage.

However, such a positive picture was neither supported by the comments, since they were exceedingly sketchy, nor by the results in the delayed post-

test. The numerical scores it seemed, in this case, exaggerated the understanding engendered by this program. At the delayed post-test stage, residual understanding was suggested by the numerical scores on Tasks 1, 4, 6, 9, 12 and 13 for C11 and on Tasks 1, 2, 9, 10, 12 and 13 for C12, but there was little supportive comment. Whilst these were not all guesses, as generally suggested in the pre-test particularly for C12, they lacked detailed explanation. Even the overview idea, that water is the source of oxygen, was not recalled. Therefore, it was very doubtful if the program worked much long-term understanding of the light-dependent reaction for either of these participants.

As with other participants, this pair rarely stated any misconceptions. Certainly at the pre-test stage none was mentioned, though commentaries were very skeletal. C12 expressed most, particularly at the delayed post-test stage on Tasks 11, 13 and 15. In the first case, C12 confused between the stages stated in the program and the light-dependent and independent reactions. In the second, ATP was acknowledged as being a high-energy molecule, but the method of its production was not. The description that 'they need to be high energy to produce ATP' may have resulted from a misreading of the task, a misconception or both, since both ATP and reduced co-enzyme are high-energy molecules. Finally, this participant was the only member of this selected group who remained unconvinced as to the source of oxygen at the delayed post-test stage. The statement that 'it must come from carbon dioxide and water' was wrong and contrasts with the clear and correct comment at the post-test stage that 'oxygen comes from water'.

7.4 Conclusions

One of the aims of this chapter was to establish whether participants' choices and confidence values bore a general relationship to their understanding of the topics tested on the tasks. From these selected pairs, the evidence was mixed, but the data suggested the following conclusions.

- At the pre-test stage, descriptions rarely related to the confidence values offered. Whilst some participants, such as P3 suggested low confidence values on tasks that they did not understand, others gave inadequate statements and conferred on these inappropriate and exaggerated values. There was, therefore, at this pre-test stage little corroboration of choices by descriptions. Indeed, it was rare to establish links between choices and target responses. When they did occur, these almost exclusively related either to chloroplast structure, or to general chemical and physical principles, such as pH and proton concentration.
- At the post-test stage, a frequent tendency to associate the correct choice, at a highly confident level, with an appropriate comment occurred - particularly for those participants where high consistent improvements featured.
- At the delayed post-test stage, correlation characteristics were less marked than at the post-test stage, because of a tendency to award high confidence levels where descriptions, albeit relevant, were not so detailed as those immediately after computer use. Nevertheless they were sufficient to support a highly confident correct choice, where choices were consistent with those of the

post-test. Occasionally delayed post-test comments were absent, which made direct correlations impossible, but the previous evidence would suggest that where choices were consistent with those in the post-test, this was because of an understanding of the reasons why.

There was, therefore, evidence at the pre-test stage, that the choice and confidence value attached to each task probably represented guesswork rather than understanding. In addition, since there was a propensity amongst some of these participants to select correct choices and to award them high confidence values (with inadequate written support), it was likely that the cognitive scoring system exaggerated cohort performance at the outset. However, since such participants counterbalanced correct choices with wrong ones at such inflated levels, ordinal values were possibly more representative.

- None of the members possessed much knowledge of the light-dependent reaction at the outset, as represented by written responses to tasks.
- Since descriptions were more often relevant in the post-test (and correlated with the scores), it was possible to conclude that both programs instituted improvement in knowledge and understanding immediately after their use, whatever the long-term changes were. It was, perhaps, possible to go further for some participants P1, P2 and P4 *Photosynthesis Explorer* users and C7, C8 and C10 *Cells and Energy* users) and to say that the evidence suggested that an

overall understanding of the light-dependent reaction was secured at the post-test stage.

- However, although all these high scoring participants continued to realise more or less the same number of correct choices very confidently at the delayed post-test stage, descriptions supporting these choices sometimes fell short of the target response, but only for the *Cells and Energy* users (C7, C8, and C10), who consistently failed to explain many of their choices of a number of essential events after the water splitting process.

What conclusions were derived from the low achievers' data, whether obtained from a participant working with either a low achiever or a high one?

- Either program had an impact on the participants' ability to complete tasks at the post-test, compared with the pre-test, stage, though this was almost always insufficient to conclude that an overall understanding of the light-dependent reaction was achieved. For users of the *Cells and Energy* program this was revealed through an increase in the number of correctly and confidently targeted choices, which reached eight or more, though without a constant theme, except on the initial process of water splitting and on the overview concepts including the nature of products and overall photosynthetic equation. However, all carried inadequate explanatory detail other than on some of the aforementioned areas. For the Photosynthetic Explorer program,

effects were also demonstrated through an increase in the number of correctly and confidently targeted choices. Nevertheless the patchiness of correct choices (as for *Cells and Energy* users) suggested in the cases of at least two participants that an overview of the light-dependent reaction had not been achieved at this stage, though their interaction with the computer perhaps made them more aware of specific events. Where the program enabled limited interaction, on chloroplast structure and design, understanding expressed either through the confidence values, descriptions or both, suggested almost nothing was understood about them. Nevertheless, data from Participant P4 (from the low scoring pair) suggested a modified conclusion, though not in relation to chloroplasts. Whilst patchiness remained evident here, the number of correct choices and the descriptions on each one possibly provided sufficient evidence for the conclusion that the simulation exercises enabled an understanding of the light-dependent reaction.

- For the low scoring pair, who employed the *Cells and Energy* program, understanding of any aspect of the light-dependent reaction was not secure long-term. Because the confidence values and number of the correct choices were reduced (and in one case to a value that was even less than the pre-test) and possessed very limited consistency between post-test and delayed post-test with reasons for these choices often returning to those of the pre-test,

with 'guesses' being acknowledged once more, any other conclusion was not justified. In fact, for the participant, who scored even less than in the pre-test, the program might have been detrimental having left a number of misconceptions. For the low-scoring partner of a mixed pair, even though comments were essentially absent and correct choices generally realised low confidence values, long-term gain was detected, since not only was there a number of choices consistent with those at the post-test stage, but also the number of correct choices was greater than in the pre-test. Amongst these consistencies were the overview topics, which possessed lower confidence values, as well as the task that sought information about water splitting and the source of electrons.

- For the low scoring pair and the low scoring member of a mixed pair, who employed the Photosynthetic Explorer program, very little evidence was secured that suggested much knowledge and understanding of the light-dependent reaction long-term. Despite the high confidence values recorded on a number of tasks for the low scoring pair, these were largely inconsistent with those at the post-test stage, which generally carried no appropriate reasons then, therefore the only aspects of the light-dependent reaction on which consistency prevailed for both participants were: the presence of thylakoids within chloroplasts, aspects of ATP synthesis and the water splitting process, with one of them (P6)

possibly holding additional knowledge about electron release and the name of the co-enzyme product. For the low scoring member of the mixed pair there was very little evidence of any recall whatsoever.

- Finally when the effects of the two programs are compared using these different pairs, *Photosynthesis Explorer* users possibly gained more at each level, as demonstrated by the more comprehensive descriptions. All participants, who used this program, gained some understanding of the process, whereas there was very limited evidence for this for the low scoring pair who used the *Cells and Energy* program. When low scoring participants were compared, the participant working with a high achiever using this program achieved more than a low achieving pair. With the low achieving participants who used *Photosynthesis Explorer*, the situation was reversed.

What did the analysis reveal about misconceptions – prior knowledge and misconceptions developed after the programs' use?

- Prior knowledge about the light-dependent reaction was absent in all cases;
- Knowledge about chloroplast structure was mixed, though misconceptions were rare;
- Misconceptions at the outset occurred occasionally, but the only relatively common one was attached to the carbon dioxide source of oxygen;
- Misconceptions resulting from the programs' use were infrequent;

If the programs delivered such varied outcomes, then a number of questions need to be asked.

- What was it in the programs themselves - the feedback and or interactive activities, for example, that delivered success or otherwise?
- Did the participants use each program in different ways?
- Were there differences in their interaction with each other and/or with the researcher, both qualitatively and quantitatively that might suggest the possible causes of the different performances of these participants?
- What misconceptions developed during programs' use?

These are the questions that Chapter 8 tackles.

Chapter 8 Participants' and researcher's activities during operation of programs

8.1 Introduction

The previous Chapter demonstrated that participants performed to varying degrees on the tasks set in the tests. Pairs were able to perform equally well, with mixed results or equally badly regardless of the program. The introductory sections of this thesis have suggested that there are a number of factors that affect learning, not least of which are the effects of cognitive conflict, collaboration – whether it is consonant or dissonant – feedback, misconceptions and prior conceptions. This Chapter sets out to analyse the data that were collected for three pairs during the running of each of the programs in order to find out possible reasons, in terms of the factors listed above, and any others, such as difficulties experienced whilst using the programs, why some participants were successful overall or on specific tasks whilst others were not. It also considers aspects of the interactions between pairs of participants and between them and the researcher in order to put forward suggestions as to why those who used *Photosynthesis Explorer* were more likely to deliver explanatory reasons for choices made. These data included those derived from video and audiotape as well as from hypercam and were:

- the times spent on the programs overall;
- the duration and occurrence of various activities undertaken, by each pair and by the researcher;
- the discourse - its balance and type – talk on or about the program, or on the topic of photosynthesis between pairs or with

the researcher, to include intervention, assistance –scaffolding and feedback

- transcription of whole discourse for one pair of participants using the *Cells and Energy* program together with equivalent parts of the *Photosynthesis Explorer* program, with commentary on cognitive conflict, quality of collaboration, effect of feedback particularly as scaffolding support and misconceptions
- transcription of sections of other pairs with commentary on cognitive conflict, quality of collaboration, effect of feedback and scaffolding, and misconceptions.

8.2 Procedure

For each pair, data were collected on audiotape, videotape and on CDs from hypercam onscreen recordings. Participant and researcher talk was transcribed from the videotape, though occasionally when it was inaudible, by audiotape instead. For those who used the *Cells and Energy* program, these data collection facilities were all that was necessary in providing an assemblage of the main events described in the Introduction. On the other hand, for *Photosynthesis Explorer*, participants were frequently required to type in answers to questions, or to carry out a variety of tasks, which the resolution of onscreen video material made impossible to read. In these cases hypercam onscreen recordings were used instead.

Tables were designed so that a record, for each pair, of the times spent on various events for every part of each program was recorded. As the video

material was run the duration of individual events was noted. These data were then summarised, with the proportion of time for each event presented as a percentage of the total time spent by each pair on either of the programs. Tables for each program, though not identical, were similar enough to allow comparison. Essentially these tables contained spaces for 'Participant activity', which was then subdivided and for 'Researcher activity', which was called 'Intervention'. For 'Participant activity' these subdivisions were for periods of 'Silence', 'Talk on the program' and on 'Talk on photosynthesis'. These main events – 'Intervention (by researcher), Silence, Talk on the program and on photosynthesis (by participants)' – were then subdivided once more. 'Intervention' included researcher 'Instruction on photosynthesis', 'Assistance with the program', 'Asking questions on photosynthesis' and 'Providing feedback/eliciting understanding/scaffolding'; 'Talk on the program' carried discourse 'Between members', 'Asking questions' (of the researcher) and 'Response to researcher'; 'Talk on photosynthesis' included the three previous elements but related to photosynthesis and the period of 'Silence' was divided differently for the two programs, since they contained some different activities. For example, *Photosynthesis Explorer* contained experimental simulations with feedback on these simulations in terms of data and events in the Mechanisms Window, whereas the *Cells and Energy* program did not, and this program included animation of events, which were separate entities, whereas animations were displayed while the practical simulation exercises were carried out in the *Photosynthesis Explorer* program. Also, the *Cells and Energy* program contained program factual feedback whereas the *Photosynthesis Explorer* program did not.

After this, the dialogue that occurred during the cognitive walkthroughs between the participants and between the participants and researcher was recorded. Next, characteristics of this dialogue were explored – both on the basis of Laurillard’s Discourse Model and in terms of collaboration and misconceptions. Finally, for comparative purposes between the programs, the dialogue and feedback were further explored to determine possible reasons for participants’ more extensive explanatory reasons for their choices in the immediate post-test for the low scoring *Photosynthesis Explorer* program users in contrast to those who employed the *Cells and Energy* program and, for the high-scoring ones, why the users of this program were unable to deliver the extensive delayed post-test comments compared with those of the users of the alternative program, *Photosynthesis Explorer*.

8.3 Numerical results and discussion

8.3.1 Results for the time spent overall and on different activities using the *Photosynthesis Explorer* program for selected pairs

All pairs (listed in order of performance – high, mixed and low) worked on this program for more than an hour and one of them for almost two hours (Pair PE1, 87 minutes and 30 seconds, Pair PE2, 118 minutes and 36 seconds and Pair PE3, 73 minutes and 24 seconds). Sample tables of results for the proportions of time spent on each activity are to be found in Appendix D. During this period the proportion of time spent in ‘Silence’ overall (working at the keyboard, manipulating the simulations, receiving intrinsic feedback from them and reading textual material – which involved generating hypotheses, setting variables, observing graphical and numerical data recording results

and checking events in the Mechanisms Window) varied very little (49.5%, 55.0% and 56.2% respectively for Pairs PE1, 2 and 3). The high performing pair (Pair PE1) spent a larger proportion of time 'Talking about the program' (7.2[5]%) compared to the other two pairs (Pair PE2, 0.8% and Pair PE3, 2.8[5]%) and they devoted a not dissimilar proportion on 'Talk on photosynthesis' (between 9.3[5] and 12.9[5]%). Similarly, the overall period of researcher 'Intervention' remained more or less constant varying between 31.2[5] and 33.7[5]%). Therefore the longest period (about half the time) was involved in some kind of work using the computer (keyboard activity, undertaking simulations, receiving feedback on them or reading), a shorter period (though still around one-third) required some kind of researcher intervention, next came participant 'Talk on photosynthesis' and finally participant 'Talk on the program'.

Within the period of silence, most time (between 26.1 and 28.5%) involved reading instructions or background material. The period manipulating the simulations and receiving feedback from them were not dissimilar either (between 2.4 and 3.2% and 8.5 and 11.3% respectively). The major difference occurred in the period devoted to keyboard activity, with the high performing participants spending a shorter period 9.1% compared to 15.6% for the other two.

Regarding the second most frequent period – researcher 'Intervention' – the proportions of time spent on three of the four subdivisions were similar amongst the group ('Assistance with the program' (between 9.0 and 10.0%),

'Asking questions' (between 4.4[5] and 6.6) and 'Providing feedback' (between 12.0 and 14.6%). The only major difference occurred in the period spent on 'Instruction about photosynthesis', with the high performing pair using 8.3%, whereas Pairs PE2 and PE3 used 1.4 and 1.2% respectively.

With regard to participant talk on the program and on photosynthesis – the least common activities – most of the talk occurred between members rather than with the researcher. However, the talk when it occurred focused on photosynthetic topics rather than on the program, except for the high performing pair where 6.1% and 5.8% of the time were spent on program and photosynthetic talk respectively.

At almost every stage of the program's use, participants were involved in all or almost all of these activities. The only exceptions to this occurred in the periods of talk, where there was either none or only occasional 'Response to the researcher' in 'Talk on the program' for Pairs PE1 and PE2, to 'Asking questions' in 'Talk on the program' for Pair PE2 and 'Asking questions' in 'Talk on photosynthesis' for Pair PE3. 'Intervention' by the researcher also occurred throughout regardless of the pair involved and for considerable periods of time. For example, the Reactants and Products topic took 13.8% of the total time for Pair PE3, though just under half (5.7%) included some kind of 'Intervention' by the researcher. The only exception was in the period of 'Instruction' where it occurred most frequently in the high scoring pair (PE1), but only in the First Look and Explorations sections of the program for the

lowest scoring pair (PE3) and in these sections for the intermediate one (PE2) as well as on one Core Enquiries topic, Electrons.

8.3.2 Discussion

These results suggested that when these selected pairs worked on the *Photosynthesis Explorer* program they all had a similar profile for the time spent on each activity and on the subdivisions within them as well as on the frequency with which they occurred. Essentially, they spent long periods on those activities integrated in the program itself (such as 'manipulating the simulations'), though data suggested that these were frequently interrupted through researcher intervention in all of the intervention subdivisions regardless of the pair selected, except that the frequency of 'Instruction on photosynthesis' was varied, with the high scoring pair (PE1) receiving this frequently, the mixed and lowest scoring pair infrequently. Only PE1 received considerable time on 'Instruction on photosynthesis' though this only accounted for 8 minutes and 38 seconds out of the total 87 minutes and 30 seconds for the program as a whole.

There was, therefore, little difference between the time spent on these different activities or on the frequency of occurrence. The one outstanding difference related to the degree of instruction. But could this be solely responsible for the different outcomes? This was unlikely since the mixed pair also held one high scoring member. Therefore, there were a number general questions that arose out of this discussion.

- How much of this expert instruction contributed to the success of the high-scoring pair of participants and was it, for example, purely instruction or was it integrated in a general discussion initiated or provoked by the participants work on the program and within their zone of proximal development (ZPD)?
- Were interventions, principally 'Assistance with the program', essential for the successful completion of sections of the program and of the program as a whole?
- Finally, why did one member of the mixed pair succeed whilst the other failed to do so?

As well as those that were more specifically about feedback events.

- Was the external feedback / scaffolding essential for successful understanding of the light-dependent process when using this program since it was provided in all sections?
- Why was the external feedback / scaffolding successful for some participants and not others when between 12.0 and 14.6% of the time was devoted to this activity?

These questions are explored in Section 8.4 on the discourse that occurred between the running of the programs and the success or otherwise demonstrated when tasks were answered.

8.3.3 Results for the time spent overall and on the different activities using the *Cells and Energy* program for selected pairs

All pairs (listed in order of performance – high, mixed and low) worked on this program took under half-an-hour to complete it (Pair CE4, 22 minutes and 28 seconds, CE 5, 25 minutes and 47 seconds and CE6, 29 minutes and 27 seconds). A sample table of results for the proportions of time spent on each activity are to be found in Appendix D. During this period the proportion of time spent in 'Silence' on the following activities 'Working at the keyboard', 'Looking at animations' and 'Reading textual material' varied a little (21.95%, 15.1% and 15.9% respectively for Pairs CE4, 5 and 6). The proportion of time spent on 'Talk on the program' was very low indeed, being between 2.5 and 2.75%, which was under 1 minute. 'Talk on photosynthesis' occupied a much longer period, which varied, with 13.8%, 16.3% and 21.0% being devoted to it for Pairs CE4, 5 and 6 respectively. 'Intervention' by the researcher occupied an even longer period still, which varied once more, with 20.1%, 24.8% and 39.5% of the time being consumed by this type of activity for Pairs CE4, 5 and 6 respectively. The only activities not included so far were the feedback events and the narrated Introduction that were available on this program, though not for *Photosynthesis Explorer*. The feedback accounted for 30.6[5] and 32.9[5]% of the time for Pairs CE4 and CE5 but only 11.0% for CE6 – the lowest performing pair and the Introduction an almost constant period of between 9 and 11%.

Within the period of silence (excluding feedback and introduction) most time (between 11.3 and 19.0%) involved reading or thinking about the tasks, with

the high performing pair spending a higher proportion of time than either of the other two. The time spent in 'Looking at animations inherent in the program' and 'Answering questions' was never more than 2% of the total.

'Intervention', which as already noted varied considerably, also varied within each subdivision amongst the three pairs. 'Instruction on photosynthesis' was nil for the mixed pair (CE5), 1% for the high scoring (CE4), and 8.4% for the low scoring, one (CE6). 'Assistance with the program' occupied either the highest (12.3 and 14.1%) period within this category for CE4 and CE5, or a high one for CE6 (11.6[5]%). Only a short period required 'Intervention' by 'Asking questions', though for the low scoring pair this was markedly higher than the other two at 5.7[5]%. 'Providing feedback' increased from 6.0% to 8.7% and 13.7% for Pairs CE4, 5 and 6 respectively.

With regard to participant talk on the program and on photosynthesis – as has already been noted 'Talk on the program' itself rarely occurred so that data from each subdivision were not recounted here. However, 'Talk on photosynthesis' was always dominated by talk 'Between members' occupying from 9.9% for the high scoring pair (CE4) to 12.8% for the mixed pair (CE5) and 14.1% for the low scoring one (CE6).

The only subdivisions not accounted for were those on program feedback. The two subdivisions here – 'Basic feedback and 'Additional feedback by calling for it' – accounted for considerable periods of time, which varied amongst the pairs. The high scoring pair (CE4) and the mixed pair (CE5) spent considerably longer involved on these two activities than the low scoring

one (CE6), so that CE4 spent 7.7[5]% on 'Basic feedback' and 22.9% on 'Additional feedback', CE5 13.2[5] and 19.7% on each, whereas CE6 only 3.5 and 7.4%.

At each stage of the program's use, participants were involved in only a few of these activities. Thus they all answered questions, read the material on all the pages before answers were attempted, looked at the summaries and received and read basic feedback, so that they were all likely to have spent similar periods on these subdivisions at each and every stage. In general pairs did so, though the periods of quiet reflection and basic feedback varied more than the other two subdivisions. Only the mixed pair spent time on every basic feedback opportunity, whereas the low scoring one rarely did so and the high scoring one dispensed with this towards the end (for reasons that will be discussed in the section on participants' discourse), so that nine out of the twelve opportunities were used. Additional feedback opportunities were also a source of difference. There was a reduction in the frequency of seeking additional information from the high scoring to the low scoring pair, who did so only on the first four topics. In areas of participant talk, 'Talk on the program' rarely took place, so instead it focused on or about photosynthesis, which occurred on almost every topic between members and on most as a 'Response to the researcher'. 'Asking questions' never occurred at any stage for the high scoring pair and rarely so for the low scoring one, though in four of the twelve topics for the mixed pair. With regard to 'Intervention' by the researcher, 'Instruction on photosynthesis' was a rare occurrence, even though the low scoring pair were occupied with it for 8.4% of their time, this

instruction was entirely delivered in the penultimate segment of the program. The only other pair (CE5) – the mixed pair – who received any instruction did so in the Introduction section. Whilst ‘Assistance with the program’ occupied all of them for around 10% of their time, it occurred infrequently for the high and mixed scoring pair. In these cases it mainly occurred in the Introduction section, but in the low scoring pair it occurred with greater frequency in half of the sections. ‘Asking questions’ was likewise infrequent, except in the low scoring pair once again, where it occurred in five of the sections. Finally, ‘Providing feedback’ occurred frequently for all pairs, occurring in seven of the sections for all of them, but overall it occupied substantially more time for the low scoring pair.

8.3.4 Discussion

These results suggested, as for the *Photosynthesis Explorer* program, that when these selected pairs worked on the *Cells and Energy* program they all had a similar profile for the time spent on each activity and on the subdivisions within them as well as on the frequency with which they occurred. Essentially, they spent long periods on those activities integrated in the program itself (from ‘Answering questions to ‘Additional feedback by calling for it’), though data suggested that these were frequently interrupted through researcher intervention in only one of the intervention subdivisions, which was ‘Providing feedback’, except for the low scoring pair where interruptions occurred more frequently by the researcher ‘Asking questions’ and ‘Assisting with the program’ as well as by ‘Providing feedback’. Essentially the only other talk involved the pairs themselves, either ‘Between each other’, ‘Asking questions’ of the researcher and ‘Responding’ to the researcher – all on the topic of

photosynthesis, rather than on the program itself. Overall, as indicated in the results section, this talk lasted for between 13.8% and 21.0% of the time and occurred at every stage other than the summaries. For the high scoring pair, frequent events occurred 'Between members' and by 'Response to researcher', but questions were never asked. For the other two pairs, talk was classified into all three subdivisions, though the low scoring one only rarely asked any questions.

There was, therefore, a general profile of participants working for the most part independent of the researcher, with limited assistance on the program itself, and talking together in pairs on photosynthesis, reading basic feedback and asking for additional feedback when required. Only the low scoring pair differed substantially from this model, with more assistance being required with the program, more terminal instruction and with limited use of the feedback available on the program.

These results suggested that one of the factors that determined success or otherwise was the quantity of feedback per se. However, although the differences in total duration and frequency of inherent feedback amongst the pairs suggested that it was perhaps the most important factor in explaining outcomes of high performing and low performing pairs, more feedback and instruction was provided by the researcher for the low scoring pair than any other. Therefore the reasons for the differences were likely to be far more complex. Because the three pairs received researcher feedback, although to varying degrees, questions needed to be asked about the kind, quality and relevance of this additional feedback, especially in relation to support for or

interruption in the overall learning events outlined in Laurillard's Discourse Model, or even in relation to the development of conflict or dissonance. It was, therefore, possible to suggest either that inappropriate intervention may impair learning or, because researcher feedback was required for all pairs, that this program could not be successfully completed at all without this input. Finally, of course, there was the performance of the mixed pair of participants who, in terms of the quantity and frequency of feedback events, carried a similar profile to the high performing pair. These differences were possibly caused by imbalanced contributions made by members of each pair during the discourse opportunities, or by an inability to comprehend the feedback or even to conceptualise the material at an appropriate level.

Therefore, there were a number questions that arose out of this discussion, answers to some of which were attempted in an analysis of the discourse events in Section 8.4.

- Were the interventions essential for the successful completion of sections of the program and of the program as a whole?
- Why did one member of the mixed pair succeed whilst the other failed to do so?

As well as those that were specifically related to feedback:

- How did the three pairs use the available feedback?
- What was the role of the feedback provided by the researcher amongst these three pairs and was it supportive or conflict promoting?

8.3.5 Comparative discussion

The *Photosynthesis Explorer* pairs took between 73 minutes 24 seconds and 118 minutes 36 seconds to complete the program, whereas for *Cells and Energy* users this was reduced to between 22 minutes 28 seconds and 29 minutes 27 seconds. Therefore the *Photosynthesis Explorer* program took between two and a half and five and a half times as long!

Photosynthesis Explorer users spent proportionately longer in 'Silence' so that every activity – 'Working at keyboard'/eq., (mean average 13.4%) 'Manipulating the simulations' (mean average 2.8%) 'Feedback from simulation activities' (mean average 9.7[5]%) and 'Reading' textual material or instructions (27.5%) used up a greater proportion of time, around 50%, compared with around half that percentage for *Cells and Explorer* users, where work at the keyboard was restricted to 'Answering questions' and simulations to 'Looking at animations', both occupying less than 2% of participants' time.

Neither group of users was occupied for a long period on 'Talk on the program', though for *Photosynthesis Explorer* users this persisted at every stage for most pairs, except for the mixed pair. Nevertheless most talk focused on photosynthesis for users of both programs, was persistent throughout, and occupied a greater proportion of time for all *Cells and Energy* users, with the highest percentage being 21.0% whereas for *Photosynthesis Explorer* this value fell to almost half (12.9[5]%).

'Intervention' by the researcher featured for the users of both programs, with participants being subjected to it for around a third of the time for the *Photosynthesis Explorer* users and between 20.1 to 39.5% of the time being tied up with this activity for those who employed *Cells and Energy*. However, whilst this intervention persisted at every stage for this program, it was almost entirely restricted in this respect to program feedback as scaffolding, except for the low achieving pair. 'Assistance with the program' was largely restricted to the 'Introduction' stage, except once more for the low achieving pair.

In terms of feedback, reference has already been made to this in terms of that from simulation activity for those using the *Photosynthesis Explorer* program. However, other feedback that made the link between experimental data and changed events in the Mechanisms Window in terms of the goal concepts sought came in the form of scaffolding almost entirely through the researcher and varied between 12.0 and 14.6%, whereas for the other program, the period of researcher feedback was less, varying between 6.0 and 13.7%. However, *Cells and Energy* users received additional feedback within the program itself that is best described as additional support or scaffolding which varied between 11.1 and 30.6[5]%. The total feedback / scaffolding period in this case varied between 24.7 and 41.6[5]% (mean average 34.3%), whereas for the *Photosynthesis Explorer* program the range was 21.7 to 25.1% (mean average (23.2%)), but the majority of this was directly concerned with numerical data and events within the Mechanisms Window, which lacked (at least for the participants) sufficient association with the goal concept which was made by the researcher's feedback and scaffolding. This accounted for

only 13.4[5]% overall for this program, which is proportionately much lower than the one-third of the time spent by those who used the *Cells and Energy* program on the equivalent activity.

Almost all these various activities featured at every stage with *Photosynthesis Explorer*, whereas for *Cells and Energy* 'Silent' activities prevailed, which included intrinsic feedback, with 'Talk on photosynthesis' and 'Intervention' by feedback from the researcher punctuating the silence. The only exception to this was with the low scoring pair, where 'Assistance with program and 'Asking questions' were additional features.

8.3.6 Conclusions

Participant and researcher activity were dissimilar when pairs used one or other of these two programs. For those who used *Photosynthesis Explorer*, multiple activities were the norm at every stage spending about half their time taking part in simulation activities, manipulating variables, formulating hypotheses, testing them and recording results and observing events in the Mechanisms Window. The other half involved some kind of talk - between each other, given to and received from the researcher about the program and photosynthesis, as well as in feedback and posing questions. By contrast, *Cells and Energy* users spent proportionately less time on talk and much more engrossed in some kind of activity with the computer, except for the low performing pair. The data suggested, therefore, that for at least two out of the three selected pairs of *Cells and Energy* users, work was an independent activity occasionally punctuated by intervention from the researcher. When

talk did occur it was almost always on the topic of photosynthesis, either between each other or as feedback from the researcher.

As well as differences in the variety of activities and periods involved with talk, there were differences in relative quantities of simulations/animations, keyboard activity and overall feedback between the two programs, with more feedback in the *Cells and Energy* program and more of the other two activities in *Photosynthesis Explorer*. Nevertheless both of them appeared capable of delivering an overall understanding of the light-dependent reaction, though only apparently with researcher input (much more for *Photosynthesis Explorer*) and, for the *Photosynthesis Explorer* users, only after candidates' lengthy exposure to the program. However, such positive effects were not always evident. It was, therefore, necessary to use cognitive walkthroughs to find evidence of sound and not so sound practice in delivering an understanding of aspects of the light-dependent reaction. By using Laurillard's Discourse Model as the basis for evaluating and contrasting the discourse behaviour of the high scoring pairs with the low ones for both programs it was possible to look for common patterns of practice within this model. Now, whilst high performance was delivered by the *Cells and Energy* program in a relatively short time, there was perhaps evidence (in Chapter 7) that users of this program were less able to explain reasons for the choices made, especially after a time delay. However, would this analysis of selected pairs support this contention? If so, were there features in the *Photosynthesis Explorer* (interactive) program that should be included in the *Cells and Energy* (tutorial) one to make it more effective in the classroom and in the *Cells and*

Energy program to enhance the efficiency of the other program's delivery? The results and discussion already suggested what some of these differences might be, so did the cognitive walkthroughs reveal more?

8.4 Results and discussion developed from cognitive walkthroughs

8.4.1 Introduction

In this section, evidence for suggesting possible answers to the questions outlined previously in sub-sections 8.3.2 and 8.3.4 was derived from cognitive walkthroughs. For the most part this evidence was taken from selected parts of the programs related to specific tasks in the tests, rather than for every event, which was excessive. The events were selected on the basis of performance of the whole cohort on the tasks related to them. Tasks were already grouped by topic – Chloroplast structure and function, Light and chlorophyll response, NADPH and ATP production and, finally, Products and overview of the light- dependent reaction, the last three of which contained topics covered in the interactive/feedback parts of both programs. A minimum of one task in each of the last three groups was achieved by sifting through them, first on the requirement for interaction or feedback, second on the overall performance amongst the cohort, third on relative performance on each program and finally on relative performance amongst the selected pairs.

8.4.2 Procedure

Six tasks were selected for further investigation: Tasks 6, 9, 10, 13, 14 and 15, which are summarised in Table 8.1.

Task number	Task focus
6	Effect of light energy on chlorophyll; the loss and replacement of electrons
9	Synthesis of ATP; the involvement of protons gradients and channels
10	Synthesis of NADPH, the involvement of electrons and protons
13	Energy profile of products of the light-dependent reaction, ATP and NADPH and oxygen
14	Use of the oxygen product of the light-dependent reaction
15	The effect of the photolysis of water on the overall equation of photosynthesis

Table 8.1 Focus of Tasks 6, 9, 10, 13, 14 and 15

Access to the concepts and scientific processes used in these tasks could only be achieved through interactive and or feedback activities when either program was used. The whole cohort scored highly on Tasks 6, 9, 14 and 15, but less well on Tasks 10 and 13. Similar performances were recorded overall on Tasks 9, 14 and 15 for participants who used either program. Differences were found on Tasks 6, 10 and 13, with *Photosynthesis Explorer* users performing much better on Task 6 and *Cells and Energy* users on Task 13. Task 10 was the task (amongst the six selected) that presented most problems for participants, with a higher proportion realising success when the *Cells and Energy* program was employed. Generally the selected pairs performed well, poorly and in a mixed pattern on each of these tasks, just as they did overall.

Tables were then prepared in which the numerical data and responses to tasks in each of the tests for each pairs of participants for both programs could be compared. A total of nine tables, each containing responses to two

tasks, for one of the equivalent pairings (high, mixed and low scoring) were prepared (an example for illustrative purposes is to be found in Appendix E. On each table, tasks were paired, so that there were three groups: on Tasks 14 and 15 (overview on water splitting and associated phenomena), on Tasks 6 and 10 (electron release from chlorophyll and electron and proton involvement in NADPH_2) and on Tasks 9 and 13 (proton channels and ATP production, and high energy of ATP and NADPH_2).

A review of the performance on each of these tasks by individual participants and by pairs was then prepared, followed by transcripts of the procedural events that possibly led to their performances, which were categorised on the basis of Laurillard's Discourse Model. These categories are:

- Apprehending structure;
- Integrating parts;
- Acting on descriptions;
- Using feedback;
- Reflecting on goal-action-feedback.

'Using feedback' events were further divided into participants' and researcher's feedback and subdivided into participants' using:

- Programs' additional feedback as scaffolding;
- Programs' basic feedback as scaffolding;
- Researcher's feedback as scaffolding;
- Intrinsic feedback from practical simulations;

and researcher's using:

- Feedback from participant (as a comment only);

- Feedback to support scaffolding.

Thus the role of feedback could be explored for both programs. In addition, further selected discourse was used to gather evidence as to the nature of the assistance required, in the *Photosynthesis Explorer* program particularly, in order to determine whether or not intervention by the researcher was essential for its successful completion. This general discourse was also used to explore why participants performed so differently in the pairs with mixed results (for either program). Finally, since there was a suggestion in the analysis of participant responses that the descriptive commentaries were more complete for *Photosynthesis Explorer* users, evidence was sought from the feedback events of the selected pairs on the selected tasks as to what might have caused differences in the richness of responses both within and between programs.

8.4.3 Introduction to results, analysis and discussion

A summary of the results for the various pairs precedes each analytical section. The analysis covers the tasks in the order 14, 15, 6, 10 and 9, which is the sequence in which the topics covered by these tasks are presented in the *Cells and Energy* program and in which participants were guided through *Photosynthesis Explorer*.

The analysis looks at extracts of the discourse, based on Laurillard's Discourse Model (Table 8.2) in order to illustrate aspects of it, such feedback (as scaffolding) and reflective events, as well as those less cognitively demanding activities, such as acting on descriptions. Reference will also be made to events that are classified as apprehending structure and integrating

parts, which refer to navigational aspects or to the presentation of material in the programs themselves.

Aspects of the learning process	Student's role	Teacher's role
Apprehending structure	Look for structure Discern topic goal	Explain phenomena Clarify structure Negotiate topic goal
Integrating parts	Translate and interpret forms of representation Relate goal to structure of discourse	Offer mappings Ask about internal relations
Acting on descriptions	Derive implications Solve problems, test hypotheses, and to produce descriptions	Elicit descriptions Compare descriptions Highlight inconsistencies
Using feedback	Link teacher's re-description to relation between action and goal to produce a new description	Provide re-description Elicit new description Support linking processes
Reflecting on goal-action-feedback	Engage with goal Relate to actions and feedback	Prompt reflection Support reflection on goal-action-feedback

Table 8.2 The role of student and teacher in the learning process (Laurillard p. 86)

In addition, collaborative activities and interactions will be identified on the basis of Lumpe and Staver's classification (Table 8.3), and the appearance of misconceptions during the operation of the programs.

Consonant	Dissonant
Providing additional help Requesting help from others Supporting another's good ideas Summarising ideas Requesting support Explicit agreement Implicit agreement Finishing another's sentence Expressing pleasure of constructed ideas (reflexivity)	Complex argument structures Not recognising another's poor idea Criticism of one's own ideas Criticism of another's idea

Table 8.3 Types of peer interactions enhancing concept development

Finally the discussion considers the overall effect of these events and prior conceptual understanding (from the pre-A level pre-test and the pre-test at A-level) on participants' abilities to target the correct response to the tasks.

8.4.4 Summary results of discourse on selected tasks for high scoring pairs

Program / pair	Tasks	Number of events per pair									
		Apprehending structure	Integrating parts	Acting on descriptions	Feedback / scaffolding						Reflecting on goal-action-feedback
					Participants using				Researcher using		
					Programs' additional feedback	Programs' basic feedback	Researcher's feedback as scaffolding	Intrinsic feedback from practical simulations	Participants' feedback to produce a brief comment	Participants' feedback to support scaffolding	
PE1	14/15	1	4	9					3	1	9
	6	6	9	10		2	1		3		10
	10			1			2	2		1	4
	9	2		4			8	1	1	7	3
CE4	14/15	4	3	2		[1]					3
	6			3	5	[3]	1			1	6
	10				2	[2]					5
	9			3	2	[6]*				2	12

Table 8.4 Number of participant / researcher activities during the discourse for high scoring pairs
* only one piece of feedback on protons read

8.4.5 Analysis of discourse for high scoring pairs

8.4.5.1 Exploration of discourse and collaboration

The high scoring pair's dialogue on material relevant to Tasks 14 and 15 for the *Photosynthesis Explorer* program (PE1), which was shared with the researcher, focused on reflective activities (9) that were at a very high cognitive level. This is illustrated by the following.

Researcher: '.....in your [original] diagram of the destination of the atoms that you drew earlier..... you are saying that some oxygen comes from water and some from carbon dioxide. However, you have just said that the oxygen comes from the water....'

Both participants: 'Yes'

P1: 'So we didn't need to balance the equation'

Researcher: 'Balancing the equation is difficult, because in order to balance it, it would be $6\text{CO}_2 + 6\text{H}_2\text{O}$ to give $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$. In actual reality it is 12 molecules of water to give $\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 + 6\text{H}_2\text{O}$, but this water is not just 6 of these transferred here'

Both participants: 'Yes'

The program took participants through a series of events that were revealed in the discourse, such as apprehending structure and integrating parts, which occurred at the outset only, so that participants were primarily involved with activities that focused on solutions to the problem as to the source of oxygen. This required the minimal of scaffolding from the researcher. Intrinsic feedback on the practical simulation involved with labelling oxygen was received during this pair's initial activities in the First Look part of the program and was reflected on during the early part of the discourse. Feedback and reflective activities occurred almost exclusively between the participants or between them and the researcher.

With regard to collaboration this pair's dialogue contained many examples of consonant activity. Right at the outset there are requests for assistance from the researcher such as:

'O.K. so we say like the oxygen from the water goes to form oxygen, that sort of thing'

'We draw O in here and then draw a line from there'.

Support also for finishing another's sentence and continuity of the dialogue indicating both explicit and implicit agreement.

P1: 'H has obviously got to go to sugar'

P2: 'H₂'

P1: 'Put 2H'

P2: 'One oxygen'.....[from carbon dioxide]

P1: 'One oxygen must go there and CO [from carbon dioxide] must go down there' [to carbohydrate]

On material relevant to Task 6, discourse events concentrated on the first three of Laurillard's list, apprehending structure, integrating parts and acting on descriptions (6, 9 and 10 events respectively), though having patiently achieved some understanding of the model, participants realised many goal-action-feedback events (10) correctly, without using the intrinsic feedback provided by the practical simulation. Much of the support came from the researcher rather than from the program itself. At this stage, problems associated with the Mechanisms Window model became apparent as is illustrated by the transcription of a segment of the dialogue below.

Researcher: 'The only thing I have to say is the pathway of electrons is shown here, though it is very poor'

P2: 'That one there' [pointing to electron source on thylakoid membrane]

Researcher: 'These represent the movement of protons here. O. K.' [proton movement through ATP synthase channel]

P2: 'Electron source is the water' [accesses hotspot to reveal $\text{H}_2\text{O} \longrightarrow \text{H}^+ + \text{e} + \text{O}_2$]

Researcher: 'Just click on there' [on run the simulation]

P2: 'NADPH and ATP' [in response to program's request for names of compound produced in the light-dependent reaction in addition to oxygen]

Researcher: 'All it's asking you to do is to click on those structures within the thylakoid membrane'

P2: [highlights hotspot]

Researcher: 'This is what is called Photosystem 2 and the other one is Photosystem 1, which are light harvesting units that lie on /in the membrane and are packed with chlorophyll. They harvest the light energy' So what do they represent?'

P1: 'Is it movement of electrons?'

Researcher: 'No, it is asking you what these are?' [pointing to the structures in the membrane]
PS1 and PS2 are called photosystems; they lie in /on the membrane and are involved in light trapping'

P1: 'Mm'

Researcher: 'I do not think the program helps you in any way to explain what these structures are. The thylakoid membrane is essentially green, but these green parts are held in a series of dot-like structures over the surface of the membrane, which are these photosystems. It is rather like extrinsic proteins in cell membranes. You've got proteins in this fluid mosaic model and these proteins are rather like this'

P1: 'Like channels'

Researcher: 'Not really'.....

Consonant activities once more prevailed: there was additional help requested and attempts made to link membrane structure to participants' current ideas, though this section of the discourse was dominated by P2. Nevertheless when they considered NADPH and ATP production in relation to electron flow, the discourse was shared an uninterrupted.

P2: 'Down' [oxygen production rate]

P1: 'Decreases it would be'

P2: 'Er'

P1: 'That means electrons.....'

P2: 'The oxygen comes from water and that reaction...'. [pointing to 'e' on the thylakoid membrane]

P1: '.....decreases it' [electron blockage]

In addition, later on in the discourse P1 summarises the idea of electrons being involved in water splitting in the goal-action-feedback loop described below.

P1: 'If the electrons are being blocked, then water is not going to be producing any more electrons, so they [water] are not going to produce any more electrons either'

Researcher: 'Correct, absolutely'

On Task 10 material, this pair generated a whole series of goal-action-feedback responses (4) that suggested the development of an understanding of the synthesis of NADPH. These events involved both participants and researcher, though with some reference to intrinsic feedback from practical simulations. They are illustrated by the following:

P1: 'If the electrons are being blocked, then water is not going to be producing any more electrons, so they are not going to produce any more oxygen either'

Researcher: 'Correct absolutely. What about NADPH?'

P1: 'That requires electrons'

Researcher: 'It does, so what would happen to that?' [NADPH]

P1: 'it would stop'

Researcher: 'It would stop as well'

Researcher: 'These are the protons. It's a very poor illustration. I do not think it works like that at all. The protons appear to be going through here [the ATP synthase] and going back here combining with an electron to make NADPH. So it is an electron, protons and NADP that produce NADPH'

P2: Shall we run it then?' [the practical simulation]

P1; 'Yeh'

Researcher: 'Have you blocked the electrons yet?'

P1; 'Yes'

Researcher: 'It does as you predict'.

So far as collaboration was concerned, there was no explicit evidence of shared involvement in the discourse to achieve a mutual understanding of NADPH synthesis, though there is implied agreement, because the member, who did not take part in this discourse, P2 immediately picked up the next stage involving ATP production.

P1: 'Now ATP'

P2: 'That depends on protons'

P1: 'The protons come from there [the splitting of water] as well'

P2: 'That's the protons' [uses arrow tool to point these out]

Finally, on the sequences associated with Task 9, the pair provided a high number of feedback as scaffolding events, essentially between the researcher and one or other of the participants (15), with occasional evidence of reflection on-goal-action feedback (3) and an initial period of apprehending structure (2). This represented a characteristic pattern described through Laurillard's Discourse Model. The feedback events continued throughout the work on this section of the program and were essentially alternated between participants and researcher. The intrinsic feedback derived from the practical simulation on the pH environment of the stroma and lumen initiated the discourse and set the scene for the feedback events that followed as is illustrated below.

Researcher: 'Now you have to do [a simulation] something that involves a bit of chemistry. The delta pH represents the difference between the two pHs of the stroma and the thylakoid lumen. So, when the pHs are the same, delta pH is zero'

[after running simulation in the light and dark and noting the pH changes]

Researcher: 'That's interesting isn't it?'

P1: 'So in the dark, there's no difference. So there are no protons being made [in the dark] because [there is] no water splitting. In the light, in this strip here [pointing to the thylakoid lumen] there are more protons so it's lower acidity because there are more protons in the stroma there are.....'

Researcher: 'That's interesting. The stromal proton concentration goes down in addition to more protons being made in the thylakoid lumen through water splitting. What must be happening to the protons in here?' [pointing to the stroma]

The dialogue held both consonant and dissonant features. These were evident in the exchanges between the researcher and participant, though they

moved the discourse on until a final consonant response between both participants and most tellingly an exclamatory comment from one of them when a solution to the problem was achieved by a series of constructed events. The following series of extracts illustrate the events summarised above.

Dissonant

P2: 'They've taken electrons from there'

Researcher: 'No, it has nothing to with taking electrons from there'

P1: 'Oh, they've joined with NADP' [which was quite a reasonable suggestion since reduced co-enzyme is produced in the stroma]

Consonant

Researcher: 'Well, yes, but something else may explain the difference. If you've more protons in here [the stroma] so as well as protons being produced by the splitting of water, what's happening to the protons in here [the stroma] if there are more protons in here' [the thylakoid] and

P2: 'They must be crossing from the stroma into the thylakoid'

Researcher: 'Correct, they are crossing the membrane'

P1: 'Oh, right!'

The high scoring (CE4) pair essentially gained the goal associated with Tasks 14 and 15 in the Task Booklet by the use of a dialogue that correlated well with Laurillard's Discourse Model, from apprehending structure (4 events) to reflection on-goal-action-feedback (3) with little if any necessity, though, to act on descriptions, such as through the generation of hypotheses. The researcher's input was minimal, except for an initial introduction to the task and a hint as to how to initiate the operation of the program to best effect.

Researcher: 'Now if you click on 'go', no not that one, 'go' itself. If you are unsure about the answer click on the phrase ATP or whatever'

Feedback and scaffolding events were entirely evident within the program itself, with no necessity for the researcher to offer any scaffolding at all.

Collaborative activities conformed entirely to a consonant pattern, with support being asked for and delivered in the form of additional feedback (2 events). The following interchange between the high scoring pair, immediately prior to and at the point of obtaining the correct response, showed just how closely the pair worked together as a team.

C7: 'I don't think it's that one'

C8: 'Which one did we.....?'

C7: 'That one' [pointing to oxygen]

C8: 'That one'

C7: 'Oh!' [exclamation on achieving the correct response]

On material linked to Task 6, this pair showed a rich series of events that concentrated on feedback and goal-action feedback as well, with additional program feedback used to guide them towards their goals. However, as the following discourse reveals, the pattern adopted was to use the program itself to discount certain responses, thereby targeting the correct ones, thus:

C7: 'O.K. the dark reactions' [followed by additional program feedback]

C8: 'It's not that one'

C7: 'Photo.....I'll try that one because I've never heard of it before' [followed by additional program feedback]

C7: 'Shall we cancel that?'

C8: 'Yes. Phosphate translocation?'

C7: 'Let's try that one' [Light Reaction Step 1] [followed by feedback]

C8: 'So it's that one'.

The researcher's role became essentially that of a bystander with only two confirmatory comments, thus

Researcher: 'You're happy with that one'

Both participants: 'Yes'

Researcher: 'So water is split into protons, electrons and oxygen. This is called the Light Reaction Step 1'.

As on Task 14 and 15 material, participants displayed consonant behaviour. Thus they requested additional assistance from the program itself and C7 found the alternatives to the question asked problematic particularly the term photosphorylation and so the dialogue continued with both implicit and explicit agreement thus:

C7: 'Er'

Both participants: 'Photophosphorylation'

C7: 'I got lost halfway through that' [word]
[after a long delay]

C8: 'Let's try the one underneath'

C7: 'O.K. the dark reactions'

C8: 'It's not that one'.

In addition there was explicit agreement with the researcher's response regarding the pair's targeting of a correct response, which was immediately followed by a confirmatory comment:

Researcher: 'You're happy with that one'

Both: 'Yes'

[Researcher comment followed by]

C7: 'Water is split into protons, electrons and oxygen'.

On subject matter relevant to Task 10, feedback, scaffolding and reflecting on goal-action' feedback events were undertaken to the exclusion of all else. The goals were accomplished entirely without any researcher intervention at all. Additional feedback opportunities were well targeted so that before each of the two choices was made, the additional information hotspot was activated for confirmation. Thus:

C7: 'That's similar to it [NADP.2H] but that [it] doesn't mean anything' [though should have done because it was called up previously when attempting to identify oxygen as a product of water splitting]

C8: 'Click on that one [NADP.2H] and see what it says'

C7: 'I am happier now. That one'.

Collaboration continued to characterise the discourse once more. Agreement between members of the high performing pair together with other consonant features, such as seeking additional help characterised the dialogue. Members of the pair showed elements of implicit and explicit agreement as well as expressing pleasure at achieving both goals correctly, without deviation at all. The whole transcript in the results section shows this, but the following extracts amplify the points and continue from the response of C7 in the discourse section.

C8: 'Yes'

[Correct, with basic feedback]

C7: 'We've already had that one' [Light Reaction Step 1]

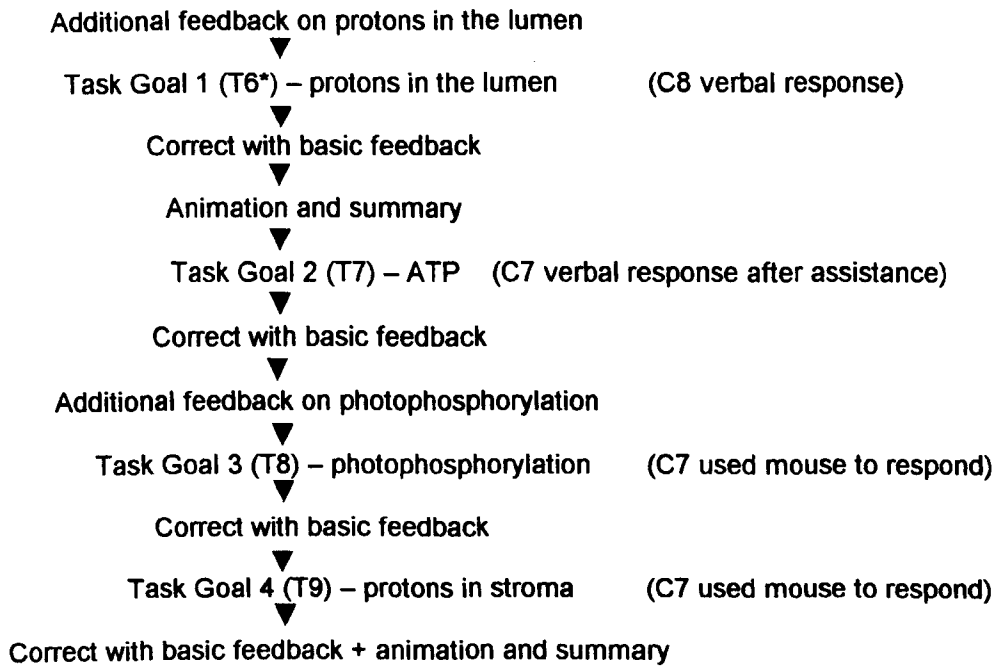
C8: 'Light Reaction Step 2' [activation of hot spot]

[additional feedback]

C8: 'Right, O.K. Hooray!'

Finally, on material relevant to Task 9 program feedback and reflection on goal-action-feedback events predominated. Additional feedback was used to

assist in targeting the correct response and the members' interaction with each other and with the researcher suggested that this was so. There were four task goals to complete and each one was appropriately targeted by reflection on previous responses in a consistent and coherent pattern, so that each goal supported progression to the next. Thus the following sequence occurred.



*T6 = number six of the nine goals overall

Evidence for interaction, other than the program's additional feedback was strictly limited, but when it did occur it was characteristic of consonant behaviour. For example, by requesting help from each other and in explicit agreement to each other's comments. This extract demonstrates this starting with commencement of Task Goal 2 – ATP.

C8: 'What do you think it is?'

C7: 'I'm not getting anywhere'

[after targeting the correct response]

C7: 'Yes'

C8: Oh, a cycle, I remember that'

C7: 'Yes'

Researcher: 'That's right, yes. ATP is regenerated in photosynthesis and in respiration [from ADP] and is used inside cells. You've looked at the use of ATP in active transport, haven't you?'

Both participants: 'Yes'

8.4.5.2 Exploration of misconceptions and cognitive conflict

With regard to the source of oxygen, the discourse events for the *Photosynthesis Explorer* pair revealed that they were unsure as to the source of oxygen at the outset, which supported their comments in the pre-test. The discourse suggested that this was resolved almost entirely independently with the aid of intrinsic feedback. For the *Cells and Energy* pair misconceptions and cognitive conflict were not issues in this respect at all, since this program did not reveal any misconceptions about the source of oxygen from carbon dioxide.

In the discourse pertinent to Task 6, the *Photosynthesis Explorer* pair revealed misconceptions about the model window, such as those related to membrane structure and to photosystems, to the flow of protons and electrons, which the discourse suggested were not resolved by scaffolding. Prior knowledge was brought to bear on these issues, but this was inadequate, even with scaffolding to support an understanding of the model. The model as presented also suggested that the electrons (rather than light energy) fuelled photolysis as illustrated by the following comment:

P2: 'Is the electron doing that? [splitting water]

During the remaining discourse on the others tasks, for the remaining pairs, misconceptions and cognitive conflict did not feature at all, except on Task 9 for the *Photosynthesis Explorer* pair. Misconceptions were evident, but the pattern of the discourse dispelled these as the researcher's scaffolding removed the conflicting ideas, until the discourse focused on the goal, which they achieved. The following extract demonstrates these events where participants explained pH differences incorrectly in terms of proton removal through combination with electrons. The extracts described below are intermittent elements, with commentary, starting with a participant's response to the researcher's question:

Researcher: '.....What must be happening to the protons in here?' [pointing to the stroma]

P1: 'They join to electrons'

Researcher: 'No, not joining. You've got a high concentration of protons in here [the thylakoid] in light and this pH goes up [in the stroma] suggesting that the proton concentration is going down, so what are protons doing in here in relation to here?' [the stroma and thylakoid lumen]

P2: 'They've taken electrons from there' [the stroma]

Researcher: 'No, it has nothing to do with taking electrons from there'

Further events led to:

Researcher: 'No, we are looking for a different idea'

P2: 'They must be crossing from the stroma into the thylakoid''

Researcher: 'Correct'.

8.4.6 Summary results of discourse for on selected tasks for mixed scoring pairs

Program / pair	Tasks	Number of events per pair									
		Apprehending structure	Integrating parts	Acting on descriptions	Feedback / scaffolding						Reflecting on goal-action-feedback
					Participants using				Researcher using		
					Programs' additional feedback	Programs' basic feedback	Researcher's feedback as scaffolding	Intrinsic feedback from practical simulations	Participants' feedback to produce a brief comment	Participants' feedback to support scaffolding	
PE2	14/15	3	2	9		1	1	1	1	5	2
	6	2	2	16		2	1	4			
	10	1	1	8		1			2		
	9	2		5		1	10	2		9	2
CE5	14/15	3	5	3	3	[1]					2
	6				2	[3]	2			2	10
	10			2	2	[2]				2	5
	9			3	1	[6]	1			4	15

Table 8.5 Number of participant / researcher activities during the discourse for mixed scoring pairs

8.4.7 Analysis of discourse for mixed scoring pairs

8.4.7.1 Exploration of discourse and collaboration

The PE2 pair (P3 low and P4 high scoring) - produced a discourse on material relevant to Tasks 14 and 15 that carried many feedback and scaffolding occurrences (9 overall), but crucially two reflecting on goal-action-feedback events in relation to the source of oxygen in photosynthesis, both in this instance by the low scoring member of the partnership. After generating ideas about the source of oxygen, the following events occurred.

Researcher: 'Now, right, is there any uncertainty in your minds or are you absolutely sure? Do you think here is any possibility of being wrong?'

P3: 'I think we might be wrong because the oxygen might combine with another of those there [oxygen from two molecules of water] to give oxygen here'

After running the simulation, this view was confirmed.

Researcher: 'Now, this is the diagram that you originally drew. Are you going to change it at all?'

P3: 'Yes, because we found that the oxygen [from water] went over there [to oxygen]

There was little evidence of collaboration on this task between participants. Whilst there were no specific examples of dissonant activities as suggested in Lumpe and Staver's list, there was one series of events that suggested one participant was not listening to the other's commentary.

P3: 'I think we might be wrong, because the oxygen might combine with another of those from there [oxygen from two molecules of water] to give oxygen there'

P4: 'Mm [doubtful] it's probably more complicated'

P3: 'Carbon definitely' [has one destination]

P4: [Types in hydrogen as having one destination and oxygen as having multiple ones, without reference to P3's comments]

Task 6 material produced a dialogue on water splitting and the role of chlorophyll that was very much restricted to acting on descriptions (16 events) and scaffolding was restricted to highlighting the hotspot 'e' and to a description by the researcher about PS1 and PS2 and the role of chlorophyll (apprehending structure and integrating parts) to which the participants failed to respond.

Researcher: 'Click on water [P3]. I think it shows that when water is split it gives, protons, electrons and oxygen. What is the source of electrons?'

P3: 'Water'

Researcher: 'You can see the flashing light input. That's PS2 and PS1 and each contains chlorophyll. Before water can be split an electron from water must be transferred from the chlorophyll. The light energy causes an electron to be excited [in the chlorophyll] and causes it to move within the membrane and it causes something to happen, which we shall see next'

No specific consonant or dissonant activities were revealed, though one participant (the overall higher scoring one P4) made very little contribution, with neither implied nor explicit agreement on any statement.

Researcher: 'What is the source of electrons?'

P4: 'Water'

P3 [clicks on hotspot 'e' on thylakoid membrane']

Researcher: 'It shows that when water is split it releases protons., electrons and oxygen. Do you agree with that Laura?'

P3: 'Yes'

On the next section relevant to Task 10, this pair acted on descriptions or the researcher did predominantly (8 out of 15 events) in response to participants' statements. The high scoring member of the pair (P4) failed to make predictions. Whilst many events could be described as feedback, they were essentially as a result of practical simulations, which failed to scaffold participants towards reflection on the mechanisms involved in the synthesis of NADP.2H – since they remained essentially descriptive. These scaffolding events were largely between one participant (P3) and the researcher, as described below.

Researcher: 'If the electrons have nowhere to go [when they are blocked] will the water continue to be split?'

P3: 'No'

Researcher: 'What would happen to the NADPH?'

P3: 'Would that increase because the electrons are needed to form NADPH so there is more build up so more could be formed?'

Researcher: 'Could be right. We will put it down if you think it would increase'

P3: 'What do you think?' [asking Holly]

P4: 'I don't know'

Researcher: 'So you could put that down – increase and don't know. Let's see what would happen then. Have you blocked the electrons, yet?'

P4: 'Yes'

Researcher: 'The oxygen production is going down. What about the NADPH production'

P3: 'It's going down as well'

Researcher: 'Is the ATP going down as quickly?'

P3: 'It is going down, but not as quickly'

Researcher: 'So which do you think is directly dependent on electron flow'

P3: 'NADPH'

This showed only the low scoring member (P3) making any real contribution. The events already described under 'discourse' demonstrate this pattern. Part of the dialogue between the participants and researcher demonstrated inconsistencies that are best described as making misconceptions manifest, rather than showing any particular features of collaboration.

On the final task, Task 9, the pair produced a discourse in which there were a large number of participant-researcher feedback events (19 out of a total of 31 events), two practical simulation feedback opportunities and one piece of program feedback with relatively few, probably only, one reflection on-goal-action-feedback event. Here the low scoring member (P3) determined that proton movement caused pH changes across the membrane, which was an intermediate goal. The final goal was never established, since participants never reflected on the feedback opportunities, particularly that supplied by the program. The following extracts demonstrate the use of the practical simulation feedback and researcher feedback to construct an intermediate goal.

Researcher: 'You will have to watch all sorts of things here. This value here – delta pH – is the difference between the stroma and thylakoid lumen pHs, so it's zero at the moment' [in the dark]

P3: 'The pH being the same in darkness'

Researcher: 'Right [after running the simulation in the light] so the pH has changed, hasn't it? Which have got the higher and lower pHs in the light?'

P3: 'The thylakoid has got the lower one'

Researcher: 'So which has got the most protons?'

P3: 'The thylakoid'

Researcher: 'Correct. So where do you think the protons have come from in addition to those produced from water splitting? That pH goes up [stroma] and that [the thylakoid lumen] goes down. Has this [the stroma] lost protons to bring about these changes?'

P3: 'Yes' [hesitantly]

P4: 'The pH has gone up [in the stroma] so it has become more alkaline'

Researcher: 'So has it lost protons?'

P4: 'Yes'

Researcher: 'So, if the pH has decreased in the thylakoid lumen, where have the protons come from?'

P3: 'Ah! The stroma'

Researcher: 'The protons are being passed from the stroma to the thylakoid in the light, which doesn't happen in the dark'

P3: 'Because the thylakoid is dependent on light'

The following part of the discourse occurs right at the end after a series of feedback events that failed to deliver a relevant reflective response from either participant.

Researcher: 'The question is: What role do protons play in photosynthesis?'

Both participants: [NO RESPONSE]

Program feedback

P3: [Read the feedback out loud] 'Is it [ATP synthase] over there?'

P4: 'Yes'

Researcher: 'The protons go through here. It's rather like having a dam of water'

P4: 'Mm' [hesitantly]

In terms of collaboration, the low scoring member made most contributions in collaboration with the researcher. The other member occasionally made overt comments illustrating implicit involvement in the discourse. For example after a long interchange between the researcher and P3, the other one showed explicit and supportive comments related to the other's ideas.

Researcher: '.....Has this [the stroma] lost protons to bring about these changes?'

Participant P3: 'Yes' [hesitantly]

P4: 'The pH has gone up [in the stroma] so it has become more alkaline'

Researcher]: 'So has it lost protons?'

P4: 'Yes'

Finally in this intermediate section of the discourse P3 uttered an explanation when there was a final understanding of proton movement.

P3: 'Ah! The stroma'

Mostly the high scoring member of this pair (P4) was non-committal and even right at the end of the discourse in response to the researcher's use of an analogy, her only comment was 'Mm'.

For the *Cells and Energy* (CE5) pair, a dialogue developed that followed Laurillard's Discourse pattern. At first, participants experienced difficulty in attaining the correct response as to the source of oxygen and therefore called for the researcher's assistance on the use of the program effectively. Thereafter feedback and scaffolding (additional feedback – 3 events) provided by the program enabled a solution to the task.

This pair generated consonant activities, such as requesting help through additional feedback and requesting assistance. Thus:

C10: 'If you try one, can you just click on it to see if it will work'

Researcher: 'That's one way of doing it. You can guess and ultimately you will be able to proceed to the next stage. However, in order to understand the light-dependent reaction you should try to solve the problem'

C10: 'Well, what's that one'

Researcher: 'When you get the right answer, the program will provide you with a description''

C10: 'O.K.'

However, it was noticeable that this discourse occurred between the researcher and one of the pair (C10 the high scoring member) and that this individual dominated much of the rest of the discourse. Out of thirteen statements made by the pair, eleven of them came from this participant. When they did alternate the discourse, this failed to suggest that they worked as a team. C10 was simply reading out the question and C9 was responding to it, so that it could be suggested that the statements produced by either participant could stand alone without reference to the other.

C10: 'To which one is the water converted?'

C9: 'I don't know'

C10: 'By the first electron carriers'

C9: 'That one' [pointing to NADP.2H]

On Task 6 material, reflection on goal-action-feedback activities predominated (10 out of 16 events) and participants realised the first choice correctly (Light Reaction – Step 1) and independently (from a previous feedback loop), but then the next event required researcher assistance in the scaffolding process.

C10: 'It was an electron and a proton, wasn't it?'

Researcher: 'But you've got two choices for protons, haven't you?'

C10: 'Protons in the thylakoid lumen and in stroma'

Unlike the work on material relevant to Tasks 14 and 15, participants worked in a consonant fashion on this task as the following events demonstrated, in relation to the destination of protons and electrons. Both showed agreement in relation to targeting and achieving one of the goals.

Both participants: 'The Light Reaction Step 1' [they then activate the hotspot on this choice before confirming their choice]

Both participants: 'Yes'

This collaborative behaviour was also illustrated by other events, but particularly by finishing each other's sentence in relation to protons.

C10: 'If they are transferred to the thylakoid lumen.....'

C9: '.....they'll be somewhere else to start'

C10: 'In the stroma'

and in a temporally separated episode on electrons, immediately after receiving basic and additional feedback on the Light Reaction – Step 1 and after a long discourse on the destination of protons.

C10: 'Name two other products that are formed in addition to oxygen' [reading part of the next question]

C9: 'Hasn't it told us'

Researcher: 'Good'

C10 'It was an electron and a proton, wasn't it?'

[after proton discourse]

Researcher: '.....but you've got one of the points right already'

C10: 'The electrons'

On sequences related to Task 10, the discourse defined a particular pattern of eliminating options in order to arrive at one correct response, though a brief

period of reflection on a previous piece of additional feedback enabled them to reach the first goal [NADP.2H]. Most of the events (7) are defined as feedback or reflection on goal-action-feedback, involving the researcher, but the level of reflection was very superficial, as is illustrated by the following after they received additional feedback from the program.

C10: 'That was to do with ATP'

Researcher: 'Is it that then?'

C10: 'No'

Researcher: 'It's definitely not that one'

C10: 'It must be that one' [Light Reaction Step 1]

Researcher: 'Well done. It's rather a legalistic way of arriving at the answer, but you've got there in the end'

The high performing member dominated the dialogue once more. Although this participant invited support from the other whose only contribution was the use of the mouse and reading out the last statement in the question (NADP).

C10: 'Electrons are passed down the electron carrier chain are used to convert.....' [reading the question]

C9: 'NADP'

C10: 'NADP. 2H. Shall we click the button first?'

C9: 'Click the button if you like'

Finally, on material related to Task 9, this pair generated predominantly feedback and reflective events (a total of 21) in this section that required four goals for completion. Additional program support was only requested once, so that assistance came from the researcher, who supported the pair frequently, though not always, towards successful conclusions. One

unsuccessful sequence occurred when participants were provided with scaffolds towards 'protons on the lumen'.

C10: 'What would you call a product of this event?' [reading question]

C9: 'It's something about protons, should we ask?'

C10: 'When it says changing compartments, does it mean they go to different places?'

Researcher: 'Yes, it's meaning the two compartments in the chloroplast represented by the lumen and stroma'

C10: 'Alright'

Researcher: 'It's asking you where do the protons go?'

C9: 'So it must be one of these' [either protons in lumen or protons in stroma]

C10: 'These were building up in the lumen before, so it must be in the stroma'

The high scoring member dominated most of the talk, which occurred with the researcher. Whilst initially the low scoring participant did enter into a shared dialogue this was short lived, but demonstrated consonant behaviour.

C10: 'What would you call a product of this event?' [reading question]

C9: 'It's something about protons, should we ask?'

C10: 'When it say changing compartment, does it mean that they go to different places?'

Eventually this consonant activity was between C10 and the researcher alone as is illustrated below.

Researcher: 'Now you should be able to do this because you've.....'

C10: '....Done it before? Was it phosphate translocation?'

Researcher: 'What did you say Laura [C10] or was it Alex [C9]?'

C10: 'Photophosphorylation'

Though at the very end, there was further involvement by the partner in relation to a comment by the researcher.

Researcher: 'So where did they start?' [referring to protons]

C9: 'They've already built up in thylakoid lumen, so they've moved somewhere else....the chloroplast lumen'

8.4.7.2 Exploration of misconceptions and cognitive conflict

As to the source of oxygen, the PE2 members were certainly unsure at the start. However, scaffolding and support appeared to resolve the issue. For the *Cells and Energy* pair, the program did not elicit such a misconception, though the high scoring member suggested in the pre-test that the source of oxygen was carbon dioxide. The only limitation in prior knowledge came with regard to the term 'cytosol' for the mixed pair. Though with regard to the light-dependent reaction this deficiency was unlikely to influence an understanding of the events in this part of photosynthesis.

Essentially the only misconception and cognitive conflict episodes that were revealed during the dialogue came in relation to the location of protons. These were on Task 6 for the *Cells and Energy* pair and on Task 9 for both programs.

On Task 6, for the CE5 pair, a cognitive conflict episode occurred with scaffolding that attempted to resolve it, though this was on the location of protons rather than on chlorophyll and electrons per se, but was an integral part of the dialogue on 'electrons'.

C10: 'Name two other products that are formed in addition to oxygen'

C9: 'Hasn't it told us' [yes, in part protons and electrons]

Researcher: 'Yes. What are you going to do, then?'

C10: 'It was an electron and a proton, wasn't it?'

Researcher: 'But you've got two choices for protons, haven't you?'

C10: 'Protons in the thylakoid and in the stroma'

C9: 'I think it's inside the lumen, don't you?'

C10: 'Yes'

C9: 'I don't know'

Researcher: 'Try asking for assistance'

C10: 'If they are transferred to the thylakoid lumen....' [referring to additional feedback]

C9: '.....they'll be somewhere else to start with'

C10: 'In the stroma'. Can you click on two of them?'

Researcher: 'Well you can, but one of the points you've got already' [the electrons]

Participants then target the incorrect destination, though the researcher, then tells them, 'The hydrogen ions [protons] are accumulating in the lumen. That's what you are saying aren't you?'

Participants: [No affirmation after targeting the correct alternative]

For the PE2 pair on Task 9, misconceptions were evident, but cognitive conflict failed to develop, so that although scaffolding occurred, conceptual difficulties with thylakoid structures were not resolved using analogous concepts in the scaffolding process. This attempted scaffold was almost exclusively with P3, the low scoring member, the other one made only one comment. These events are described below.

Researcher: 'Here you have to predict something about punching a hole in the thylakoid membrane'

P3: 'There would be an increase in the high-energy molecule, because when we blocked [the electron flow] they [the high-energy molecules] decreased, so if we put a hole in it, they [the electrons] could move therefore they [the high-energy molecules] would increase'

Researcher: 'You are on the wrong track here. Let's consider your AS work. If you have a cell membrane that's involved in active transport, which can move things against a concentration

gradient, what would happen to the concentration of chemicals on either side of the membrane if the cell were to die?’

P3: ‘They would become the same’

Researcher: ‘Now, here you have accumulated protons and this is because the high energy molecules are able to pump the protons across the membrane. If you like to actively pump them across. If you punched a hole in it, what would happen to the protons, then?’

P3: ‘They would just move wherever they want’

P4: ‘Mm’ [unsure]

Researcher: ‘Which would be where in this case?’

P4: ‘Into the stroma’

Whereas for the CE5 pair the issue was resolved as is demonstrated below.

C10: ‘It must be the lumen. Before it didn’t make it clear did it? It said they already built up in the lumen’

Researcher: ‘The program did, didn’t it?’

C10: ‘Yes, it’s almost contradicting itself’

Researcher: ‘Yes. They accumulate in the lumen during photolysis, but the above feedback describes that more protons move across the membrane as electron transfer takes place. These electrons lose energy as they do so between the carrier molecules, so that between each oxidation-reduction reaction the energy is used to pump [more] protons from the stroma’

C10: ‘O.K.’

8.4.8 Summary results of discourse on selected tasks for low scoring pairs

Program / pair	Tasks	Number of events per pair									
		Apprehending structure	Integrating parts	Acting on descriptions	Feedback / scaffolding						Reflecting on goal-action-feedback
					Participants using			Researcher using			
					Programs' additional feedback	Programs' basic feedback	Researcher's feedback as scaffolding	Intrinsic feedback from practical simulations	Participants' feedback to produce a brief comment	Participants' feedback to support scaffolding	
PE3	14/15	3	5	15		2	4	3		8	1
	6	2	6	8		1	1	3		2	
	10	1	3	5		1	1	2		2	
	9	2		11		2	1			4	1
CE6	14/15	1	3	2	1	[1]				2	2
	6				1	[3]					6
	10		2	12	3	[2]	3			4	7
	9		2	15		[6]	6			7	17

Table 8.6 Number of participant / researcher activities during the discourse for low scoring pairs

8.4.9 Analysis of discourse for low scoring pairs

8.4.9.1 Exploration of discourse and collaboration

On material related to Tasks 14 and 15, the *Photosynthesis Explorer* pair (PE3) generated a prolonged discourse in which most of the activities were on apprehending structure (3), integrating parts (5) and acting on descriptions (15). Whilst there were feedback events between the researcher and participants that maintained the discourse, the event that secured the source of oxygen is described below, which included intrinsic feedback from the simulation.

Researcher: Where does it appear ? [oxygen in labelled water]

P6: 'In the oxygen'

Researcher: 'And that's not what we said'

P6: 'Nope'

For this pair there are several examples of the members working as a team.

A typical one was a request for assistance:

P5: 'I think it's carbon dioxide' [as the source of oxygen]

P6: 'Yes'

P5: 'Plus two hydrogen. Oh, no I don't. I think it's the hydrogen plus that carbon and then those two [pointing to oxygen in water] go to oxygen'

P6: 'Yes, that [water] and carbon[from carbon dioxide] go over there' [pointing to carbohydrate]

P5: 'Shall we write them in there?'

On sequences relevant to Task 6, the researcher's contributions were mainly restricted to assisting in events such as integrating parts within the model (8 events) rather than in scaffolding towards the goal. The single event that provided feedback related to the goal was:

Researcher: 'That's Photosystem 1, which is a light harvesting unit and this is another one Photosystem 2. There are lots of these in the membrane and they harvest the light energy and in so doing, they energise an electron. Click on water. Water is split into oxygen, protons and electrons.....'

Consonant activities were restricted to asking for help from the researcher rather than in collaboration between the members. For example, both participants requested help from the researcher in establishing structures within the thylakoid membrane.

P5: 'Is it the black things that are moving, the electrons?'

Researcher: 'That's a good point. They are in fact the protons[which move through ATP synthase]. The only thing you can see is the electron flow from water'

P6: 'Is it that thing there?'

Researcher: 'Yes. These are the electrons and these are the protons and these [the protons and electrons] produce this compound [pointing out NADPH] and the protons are used [as well] in some way to drive the production of ATP'

On Task 10, this pair almost exclusively limited the discourse to acting on descriptions (5 out of 15 events), to integrating parts (3) and to responses to intrinsic feedback (2) provided by the practical simulation, thus there was little evidence of scaffolding and reflection towards understanding, as for example in this extract from the simulation, which also illustrates the shared dialogue that occurred.

P5: 'Run it until it stabilises'

P6: 'ATP level' [does not change]

P5: 'The oxygen decreases'

P6: 'The whole lot decreases'

Researcher: 'Which of the two decreases, ATP or NADPH decreases most rapidly?'

P5: 'The NADPH'

Researcher: 'That looks as though it is directly dependent on electrons. Are these the results that you expected?'

P6: 'No'

The discourse was shared with the researcher and whilst members made predictions and responded to the researcher there were no specific consonant or dissonant characteristics.

Finally on material relevant to Task 9, the pair secured a short discourse starting with apprehending structure (2), acting on descriptions (11) intrinsic feedback (1) researcher-participant feedback (6) and then researcher-participant feedback and finally (possible) reflection on these activities

produced a coherent series of events. The researcher's scaffolding process enabled participants to move from intrinsic feedback to a consideration of the effect on proton flow through membrane damage.

P6: 'In the light there was a difference [in pH]. In the dark they levelled'

Researcher: 'So which pH goes up and which goes down?'

P5: 'The stroma goes up and the thylakoid [lumen] goes down'

Researcher: 'So what is the concentration of the protons in the thylakoid compared to the stroma?'

P5: 'It is acidic' [correct, but a stage too far]

Researcher: 'So the proton concentration has increased [in the thylakoid]. So the protons have moved from here [the stroma] to here [the thylakoid lumen]. That's fuelled by the energy of electrons pumping protons from here to here. When they reach a critical level, they cause this channel [ATP synthase] to open and ATP is made'

[hole punched in membrane]

Consonant events characterised the interactions during the discourse. There were no disagreements between the participants and although the dialogue between them was frequently interrupted by the researcher it showed implicit and explicit agreement with what the other had said. These events are illustrated below.

Researcher: 'What would the oxygen production rate be with an intact membrane?'

Both participants: 'High'

Researcher: 'ATP level?'

Both participants: 'High'

Researcher: 'NADP.2H level?'

Both participants: 'High'

Researcher: 'What would happen if you punched a hole in the membrane?'

P6: 'They'd both go down'

Researcher: 'What would happen to the pH difference?'

P5: 'It would be neutralised'

The *Cells and Energy* pair (CE6), as for the high- and mixed -scoring pairs on matter pertinent to Tasks 14 and 15, followed a path from apprehending structure to reflecting on goal-action-feedback as the others did, though they not only failed to use any additional feedback, so that in order to reach their task goal, scaffolding came through the researcher. The reflection-on-goal-action-feedback was also unconvincing as the dialogue below illustrates. One of the participants (C11) intuitively suggested oxygen as the product initially, but the discordant dialogue, together with the movement of mouse through all the alternatives, failed to capitalise on this.

C12: 'It's going to convert.....'

C11: 'Oxygen'

C12: 'No it's the sunlight'

C11: 'It doesn't convert it [water] to the sugar' [additional feedback briefly appeared, but not read]

C12: 'Not straightaway, no, not ATP' [additional feedback briefly appeared, but not read]

C11: 'No, I don't know what the NADP.2H is' [additional feedback briefly appeared, but not read]

Researcher: 'Do you want to know?'

C11: 'Yes'

Researcher offers explanation and then 'Rhys, you have made an intuitive suggestion as to what the answer might be'

C11: 'I said oxygen, but then.....'

Researcher: 'Why don't you try to see whether you're right or not? Click into the box, not the word oxygen'

[receive feedback + additional feedback as requested by researcher, though not read]

Researcher: 'Are you happy with that?'

C11: 'Yes'

On Task 6 material this pair produced a discourse that was generally independent of the researcher, consisting predominantly of reflection on goal-action-feedback events (6 out of 7) in order to achieve the first of two goals in this section. However, these were all rather superficial as is illustrated in the collaborative features of the discourse in the paragraph below. In addition, additional feedback was not requested at any stage, just as for the first task on photolysis. An analysis for the second goal was only included for participants' determination of the electron product from the process of photolysis, which was only one aspect of the second goal. The remaining parts of the discourse are incorporated into the analysis of the next two tasks, first Task 10 and subsequently Task 9. The goal-action-feedback events for the first goal are included in the section on collaboration, since they best illustrate interaction between participants. Nevertheless one of the participants (C11) was directed to the 'electron' response by the researcher described in the following sequence in which additional feedback was reflected upon.

Researcher: 'If you want to click in that description [Light Reaction Step -1] it will tell you more about the Light Reaction – Step 1'

C11: 'That's basically the question we've just answered'

Researcher: 'And you've got it right, haven't you? I hope that helps'

C11: 'It gives a clearer picture'

C11: 'That one' [electrons]

For the low scoring pair, collaboration was best shown by the support that one member provided to the other's comments.

C11: Identify the process that allows this change' [reading question]

C12: 'It's not the dark reaction'

C11: No that comes later. We've only done one thing, so it can't be Step 2 can it?'

C12: 'It could be the light-dependent reaction Step 1 or 2. We've already done one step to oxygen'

C11: 'So what do you reckon?'

C12: 'I don't know'

C11: 'I think it's the first one'

C12: 'Give it a go'

However, towards the end of this section, there was exclusion of one of the pair (C12) from the interactions that occurred between the researcher and the other participant, which is described below after they received additional feedback on the Light Reaction – Step 1.

C11: 'That's basically the question we've just answered'

Researcher: 'And you've got it right, haven't you? I hope that helps'

C11: 'It gives a clearer picture'

C11: 'That one' [electrons]

With material on Task 10, the discourse analysis starts from participants' determination of the other product of water splitting and its location in either the lumen of the thylakoid or in the stroma of the chloroplast. Up to this point, their discourse consisted of a series of descriptive episodes (totalling 12) until the researcher intervened, when program feedback and scaffolding as well as assistance from the researcher played a more prominent role. Occasionally reflection on goal-action-feedback events entered the discourse, but it all lacked coherence and relevance, so that a pattern failed to emerge. The following transcript commences after a series of descriptive episodes subsequent to which the researcher suggested that they used additional feedback. The goal was protons in the lumen and the first two questions posed by C11 were in response to additional feedback on NADP.2H.

Researcher: 'Do you have any questions?' [after additional feedback on NADP.2H]

C11: 'Is that formed later on by any chance? Is it used in the dark reaction?'

Researcher: 'Yes'

C11: 'So what do you want to go for? I don't think it's ATP'

C12: 'No'

C11: 'I'm not sure about the proton'

Researcher: 'What's the question asking you? May I ask that you go back to the NADP.2H feedback and read it!'

Researcher: 'So?'

C11: 'It is formed from NADP'

Researcher: 'Yes, but when water is split, what is it split into?'

C12: 'Two hydrogens'

Researcher: 'Protons. But where do you get these protons?'

C12: 'In the thylakoid lumen'

Whilst the members of this pair shared the discourse, they appeared to make their choices almost at random, without being either consonant or dissonant. Nevertheless they were unwilling to seek advice unless urged to do so. Participants, therefore, started their dialogue without reference to the feedback received to the water splitting process and the release of protons set out in the results for Task 6.

C11: 'That one I reckon' [NADP] [the first on the list]

Researcher: 'Why do you think that one, Rhys?'

C12: [ignoring researcher's comment] '[Do] you think it's the top one Rhys?'

C11: 'I think it's the second of the two' [NADP.2H]

C12: 'With the 2H because you get the hydrogen coming off'

C11: 'I remember that [NADP.2H] from the pre-test. Give it a go'

Researcher: 'It is telling you that you are wrong. Do you want to find out more information as to why this was?'

C11: 'Do you want to?'

C12: 'Yes'

On Task 9 material, the long discourse generated a very complex series of events in which acting on descriptions (15 events) played the major role as did integrating parts (although restricted to 2 prolonged events) resulting from little used feedback opportunities previously. Feedback events here occurred largely between the researcher and members of the pair as a result of misconceptions or included basic feedback from the program to their achievement of a correct response. Additional feedback from the program was never requested. The researcher also interrupted the discourse in order to elicit recall of earlier events. Reflective instances were substantial (17), but largely concerned remedial activities and correct responses were frequently achieved with reflection at a level commensurate with the elimination of responses (identified as acting on description in the complete transcript) because they had been targeted previously. This approach is illustrated below.

C12: 'I'm going to go for ATP, because it's not NADP.2H or oxygen' [answers previously targeted]

Researcher: 'What's the question asking you?'

C12: 'Identify the next intermediate'

C11: 'That's not being used in that' [pointing to 3C – sugars] Go for ATP'

C12: 'But then it could be fructose phosphate'

Researcher: 'You are way off on that one'

C12: 'Is that 3C sugar a 3 carbon sugar, is that what it means?'

Researcher: 'Yes, it means a 3-carbon sugar, absolutely. So the question is asking you, what is the next intermediate in the pathway from the list below?'

C12: 'What do you think?'

C11: 'I don't know. I'd go for one of these two' [ATP and NADP.2H]

C12: 'I'd say ATP'

As illustrated on other tasks, the pair shared the discourse.

8.4.9.2 Exploration of misconceptions and cognitive conflict

There was uncertainty about the source of oxygen for pair PE3, even though the data produced from the simulation was confirmed by both of them. In this concluding section at the end of the Reactant and Products part of the *Photosynthesis Explorer* program P6 failed to respond.

Researcher: 'You are still saying at the moment that some oxygen is still released from carbon dioxide to form oxygen. [gas] So what is going to sugar?'

P5: [Types in carbon]

Researcher: 'But is it carbon or carbon dioxide that goes to sugar?'

P5: 'Carbon dioxide'

However, misconceptions and cognitive conflict essentially revolved around the concepts of protons and their location primarily for the CE6 pair using the *Cells and Energy* program. For this pair misconceptions were revealed when material relevant to Task 6 was accessed. At this stage, they failed to reach a stage where cognitive conflict was evident. Nevertheless prior knowledge was an issue in relation to hydrogen, protons and hydrogen ions. At an early stage in the dialogue C12 made the following statement:

C12: 'With the two hydrogen, because you get the hydrogen coming off'.

Later after receiving additional feedback using the symbol H^+ the other participant states:

C11: 'I'm not sure about the proton'.

Further on the researcher refers to the splitting of water and C12 returns to a reference to hydrogen, with researcher's correction.

Researcher: 'Yes, but when water is split, what is it split into'

C12: 'Two hydrogens'

Researcher: 'Protons, but where do you get these protons?'

C12: 'In the thylakoid lumen'

On Task 9, the program made evident confused ideas that caused cognitive conflict, emanating from the location of protons, which was not resolved through extensive scaffolding provided by the researcher. The following extract illustrates this problem.

Researcher: 'You said [in answer to a previous task – Task 3] that the protons ended up in the thylakoid lumen' [the only choice was protons in the lumen]

C12: 'They're already there, so they're not going to change'

Researcher: 'Well, that's the question'

C12: 'They change compartments' [participant assumes that they cannot do so because they are all in the lumen from the photolysis of water]

[correct response achieved]

Researcher: 'So how are the protons getting into the thylakoid lumen from the stroma?'

C11: 'When they were first split, so am I on completely the wrong track?'

Researcher: 'No, carry on'

C11: 'When they come in from the outside' [when the protons are released by photolysis]

Researcher: 'Where do the protons originally come from?'

Both participants: 'Water'

Researcher: 'And at the same time, what did you get as well as oxygen?'

C12: 'Hydrogen' [protons]

C11: 'Electrons'

Researcher: 'You get electrons as well. One question that has not been satisfactorily answered so far is, where do the electrons go when water is split?'

[NO RESPONSE]

Researcher: 'You know something about the protons don't you?'

[NO RESPONSE]

'Where do the electrons go?'

C11: I can remember the diagram?'

[RETURNS TO ORIGINAL MODEL]

C11: 'O.K.'

Researcher: O.K. You've got the electron transport chain here and you've also got chlorophyll as well. When water is split into protons and electrons [and oxygen], the energy derived from the electrons [lost from chlorophyll] is used to pump the protons across the membrane. The electrons [from water] move into the chlorophyll molecule from water. These are [subsequently] energised there [by light energy] and then moved through the carriers'

[NO RESPONSE]

C12: 'I'm going to go for ATP....'

The only other misconception occurred with the PE3 pair also about protons, but this time related to the nature of the thylakoid membrane.

Researcher: 'Would you say that the oxygen would stop or continue?' [if you blocked the electrons]

P6: 'Continues'

P5: 'That [NADPH] would stop [appears to be linked to electrons in the model]

Researcher: 'What about ATP?'

P5: 'That would continue'

8.4.10 Results, analysis and discussion for pairs on Task 13

A trawl through the discourse between participants and between them and the researcher indicated an occasional implied or explicit statement on these high-energy molecules, though these were very restricted in number. For example, for the mixed pair who used the *Photosynthesis Explorer* program, the terminal part of a long discourse on the use of protons in the synthesis of ATP, the researcher provided a final statement.

'The electrons are energised, the protons accumulate in the thylakoid lumen and they move out through here [the ATP synthase] to produce ATP. You also get NADPH and these compounds are used in the LIR to produce sugars'

For the *Cells and Energy* program, only one implied statement was found which, as for the mixed group who used the *Photosynthesis Explorer* program, came at the end of a section. For this low-scoring pair the researcher commented.

'.....it's rather like water falling down a waterfall. The protons travel through here [the ATP synthase] and the energy, which is being lost, is used to drive the production of ATP. So ATP is made, as well as NADPH as a result of the light trapping process'

Within each program there was some information about these compounds, though in the *Photosynthesis Explorer* program this appeared in the form of pages of descriptive material only, which was read though not discussed. On the other hand, for *Cells and Energy* facts about these compounds came as a result of program feedback events either after identifying the named product goals, or in the process of engaging with them. These differences may explain the better performance of the whole cohort that used the *Cells and Energy* program. Thus for *Photosynthesis Explorer* in the section called Energy Store: Energy Compounds on pp. 4 and 5 the following description appeared:

'There are a few compounds known to store energy chemically in biological systems. Two of these are: ATP...[and]....NADPH....which holds two energised electrons.....' and in The Electron section, pg. 1 '.....In the light reactions, the high energy and reducing agents ATP and NADPH are formed'.

These were the only occasions that provided these facts, though participants were not expected to derive or deduce this knowledge in any way.

On the other hand, *Cells and Energy* users received generally more information (if they used basic feedback events that resulted from attaining a correct answer) and sometimes substantially more (if they used additional feedback) when they were engaging with various goals. Whilst, as with *Photosynthesis Explorer*, tasks were never explicitly about the energy content of these two programs, facts were supplied after an interactive process. Thus if participants activated the hotspots NADP.2H and ATP information about these two chemicals appeared. For example:

'It [ATP] is often referred to as the energy currency of the cell. ATP is consumed by energy requiring reactions'.

Similarly in the narration on photophosphorylation reference was made to:

'This compound [ATP] is now available for use in energy consuming reactions'.

When feedback was received on the correct responses to 'ATP' and 'photophosphorylation' similar descriptions occurred. There was, however, no specific comment on the energy content of NADPH in either any program feedback events, or indeed in any researcher feedback, though those who possessed chemical understanding from program feedback events could assign knowledge of this fact to it.

8.5 Discussion

8.5.1 Introduction

Successful learning is affected by a number of factors, not least of which are prior knowledge and misconceptions, and the situation in which learning takes place as, for example, individually or in groups. The psychological processes considered to achieve this vary from those based on the behaviourist tradition to a constructivist or even social constructivist one, from test and practice to

one of comprehending the processes by which learners not only come to understand and to know what it is that they understand, but also how new knowledge is constructed, which is metacognitive and self-regulatory. One possibility in the constructivist mould, as Piaget suggested, is that learning will occur when learners suffer from disequilibrium or cognitive conflict in the construction of this new knowledge, another is that it is established as scaffolding occurs within learners' zones of proximal development, as suggested by Vygotsky.

Computers are considered by many to be important tools for learning and authors have proposed the value of different computer tools from data processors to tutorial programs. One way in which the merit of these programs may be assessed is by using Laurillard's Discourse Model in which learning establishes itself in learners using feedback as scaffolding and reflecting on previous actions, as well as more basic activities, such as apprehending structure, integrating parts and acting on descriptions. The use of these categories makes assessment of scaffolding and cognitive conflict easier to recognise.

Additionally, when learners work in groups their verbal interactions make these events observable for inspection and debate in order to evaluate not only merits of one theoretical position or another, but also the educational value of the computer as an instructional tool.

The discussion below develops from the analysis made previously on twelve participants' activities, when working in pairs on material in different programs

that is relevant to five tasks on the light-dependent reaction, Tasks 14, 15, 6, 10 and 9. It looks at the effects of the various factors outlined above:

- misconceptions – both before the programs' use and developed whilst they were employed;
- discourse of the pairs viewed from Laurillard's perspective;
- participants' sharing of the dialogue, together with the involvement of the researcher;
- cognitive conflict, its resolution and scaffolding;

on learning as assessed through participants' performance on the five tasks in the post-tests after they used the programs.

For clarity, each of the tasks is discussed separately incorporating each of these elements, as they were in the analysis.

Before the discussion starts, what of prior knowledge on general aspects of photosynthesis related to the light-dependent reaction as assessed by the pre-A level test at the outset? Using the raw scores as a basis on which to judge participants' general understanding about leaf and chloroplast structure as well as about energy there were some differences that might have influenced their ability to understand the light-dependent reaction regardless of the ways in which they used the program. Two participants who used the *Photosynthesis Explorer* program that is P6 (who was a member of the low scoring pair in the A-level tests) and P3 (the low scoring performer in a mixed pair), only scored half marks. Two more, both from the low scoring pair using

the *Cells and Energy* program (C11 and C12) held misconceptions about energy, though they both attained more than half marks.

In the pre-test at A-level four participants, P2, P4 and P6 and C10 revealed the same misconception. This concerned the source of oxygen as carbon dioxide rather than water. The statements made by them might be considered to represent a stronger and perhaps more firmly held misconception than when it was revealed by others during the course of the cognitive walkthroughs.

8.5.2 Tasks 14 and 15

The *Photosynthesis Explorer* program was designed to consider a problem posed around two possible sources of one of the products of photosynthesis. This product was oxygen from either carbon dioxide or water. The program provided participants with practical simulations on the effects of isotopically labelling various molecules in order to discover the source of oxygen. For those who used this program, the evidence suggested that feedback and reflection were important in providing participants with knowledge that the origin of oxygen was water. All participants revealed at the outset that they were unsure as to its source and those participants who revealed a misconception in the pre-test provided no further evidence that they held a firm conviction about this. All participants used the practical simulation and the intrinsic feedback received from it to alter their original ideas.

The collaborative profile for the high and low scoring pairs suggested that they worked consonantly, though the behaviour of the pair with overall mixed results suggested dissonance. Consonant behaviour appeared to be most marked in the high scoring pair's dialogue. One member of the pair (the high scoring one) seemed to have a disinterest in the other's responses by entering answers to questions posed by the program without reference to the other.

Misconceptions were factors that revealed themselves during the course of the discourse. Certainly participants held conflicting ideas as to the source of oxygen, some considering it as coming entirely from carbon dioxide and others that it came from both carbon dioxide and water. These conflicting views developed during the construction of a model appeared to be resolved as pairs worked through the program. For the high scoring pair this resolution evolved through a dialogue that required the minimum of scaffolding by the researcher, except for consideration of how the equation should balance if water was the source. For the other two pairs, resolution was achieved through scaffolding provided by the researcher, though the evidence from the analysis was unconvincing for the low scoring pair, especially for P6, who took no part in the final summary comments on this topic.

Thus in all cases the use of the program should have revealed an understanding of the source of oxygen in the post-tests. There was, though, some uncertainty about this with regard to the low scoring pair, especially P6 who failed, as described previously, to respond to the summary questions

posed by the researcher. The tests, in the Test Booklet, did indeed reveal that all participants held an understanding about photolysis in the immediate post-test, though in this one case (P6) this was not secured at the delayed post-test stage. It was possible that for this participant the program failed to convince this individual about the possible source of oxygen, because of the misconception revealed in the pre-test. The only other participant's results about which there could be some doubt was P3, the low scoring member of the mixed pair, whose confidence scores and comments were unconvincing. However, since this participant took part in most of the discourse this anomaly cannot be explained at this stage.

The high scoring and mixed pair of the *Cells and Energy* program users followed a pattern that in all essentials correlated well with Laurillard's Discourse Loop, especially for the high scoring pair who did so using scaffolding through feedback, both basic and additional, supplied by the program. Scaffolding suggested that it provided the structure on which the first goal was achieved. The same applied the mixed scoring group, too, though their approach suggested the prospect of a guessing strategy to achieve it, which the researcher gently countermanded. The low scoring pair's activities suggested a more hesitant exploratory approach whose discourse was supported by the researcher, since members' activities appeared to be largely intuitive and random.

Consonant characteristics were most marked during the dialogue between members of the high scoring pair, less so for the mixed one and least in the

lowest achieving pair. With the mixed pair particularly intervention by the researcher suggested a changed, more productive, strategy that sought for and used additional feedback in order to provoke a search for an appropriate answer to the product of the photolysis of water. However this search tended to be by the high scoring member of the pair (C10) only. The lowest scoring pair's approach suggested a less successful learning strategy that neither employed synergy between the members or between them and the researcher.

Misconceptions and cognitive conflict in terms of the source of oxygen were not issues that appeared to impair progress or to stimulate debate in this section of the program.

With this program, therefore, on this topic, learning appeared to be established through scaffolding alone (in which cognitive conflict played no part) at least for one of the pairs. In contrast, for the mixed pair, this discussion suggested that scaffolding was effective, though only for the high scoring member, because the low scoring one only showed limited involvement in the discourse. Finally the low scoring pair's approach was not expected to promote success.

Generally the results in the post-tests supported this view. The high scoring pair were very confident in their responses in both post-test on both tasks, the mixed scoring pair obtained different results though consistent with the prediction and the low scoring pair a better than expected result in the first

post test, where both pairs achieved the task correctly very confidently, but both failed to do so in the delayed post-test.

8.5.3 Task 6

The sections of the *Photosynthesis Explorer* program that were relevant to Task 6 were intermingled with material on Task 10 and, as far as possible, this discussion as in the analysis separates these events.

The discourse was not considered to conform to a series of events leading to reflection-on-goal-action for any of the pairs. There was a focus on apprehending structure, integrating parts and acting on descriptions rather than the goal because of the problems participants seemed to show in understanding the model in the Mechanisms Window. This was particularly evident with the high scoring pair where participants made a determined attempt to understand this, with assistance from the researcher. This problem was one that occurred on numerous occasions with the likelihood of affecting all participants' pursuance of a number of other goals.

Interactions suggested consonant characteristics for the both high and low scoring pairs not only between the researcher and participants but also between them, though for the mixed pair, the high scoring member (P4) seemed to delegate most the discourse to the partner's interactions with the researcher. As noted in the preceding paragraph there was a concentration on apprehending structure, integrating parts and acting on descriptions, but interactions were prolonged and represented the major components on this

topic, especially for the high scoring pair. Nevertheless their expressed views suggested that none of them held a conceptual understanding of the structure of the membrane or of the events involved within it. This was suggested in ever more graphic detail when other topics are considered in this discussion.

So far as misconceptions and cognitive conflict were concerned, these mainly revolved around the structures represented by the model. These were insurmountable problems and were a recurring theme. What, for example, represented the flow of electrons and protons and what exactly were PS1 and PS2? With the high scoring pair this was not resolved even with the use of reference to AS work on cell membranes by the researcher. With the other pairs, scaffolding was restricted to researcher assistance in directing participants towards the relevant hotspots and program feedback on the identification of structures in the membrane or events that occurred in relation to them. These, however, were restricted to simple equations, such as a representation of the photolysis of water or even just a name or an abbreviation that required researcher amplification. One participant from the high scoring pair (P2) appeared to hold the misconception that it was electrons that were causing water to split. This participant, after the researcher's negative feedback followed by an explanation of the role of chlorophyll, made no further formal contribution to the continuing discourse. Interestingly this misconception was recorded in the immediate post-test.

As a result of the discourse events and the failure to understand the chloroplast model it was unlikely that participants would hold an

understanding the role of chlorophyll in the water splitting process. In fact, the post-tests suggested that this was so. Whilst most participants targeted the correct response in the post-tests their comments were restricted either to the equation revealed by the 'e' hotspot or to a description of these events. Only P4 wrote something more that corresponded to a piece of researcher feedback on the effects of light energy on chlorophyll.

Researcher: 'You can see the flashing light input. That's PS2 and PS1 and each contains chlorophyll. Before water can be split an electron from water must be transferred from the chlorophyll. The light energy causes an electron to be excited [in the chlorophyll] and causes it to move within the membrane....'

Cells and Energy users concentrated their efforts on feedback and reflection on feedback opportunities with scaffolding through the program supplying most of the needs for the high and mixed scoring pairs. The approach taken by the high scoring pair suggested a process of elimination. Although additional feedback was used on three separate occasions to target the first goal in this section on photolysis, receiving it on the dark reactions and photophosphorylation and thinking about it for phosphate translocation, the approach lacked focus. Eventually one participant asked for feedback on the Light Reaction-Step 1 so that they appeared to stumble almost fortuitously on the answer to the next task about electrons. The approach taken by the pair with overall mixed results suggested a quite different feedback strategy, albeit supported by the researcher, that initially requested independently a relevant item of additional feedback on the Light Reaction – Step 1. This was followed by a period of intense debate that might have secured a correct answer to the location of protons by requesting additional feedback. However, intervention

by the researcher precipitated their targeting of a relevant item of additional feedback that directed their response to one on electrons. For the low scoring pair reflections suggested superficiality. However, a request to them by the researcher to ask for additional feedback after realising the first goal enabled them to target a second.

The evidence from collaborative episodes suggested that all pairs were working consonantly, with a sharing of ideas, other than the low scoring pair. Here the absence of any involvement by one participant, C12, towards the end of the discourse about electrons seemed to suggest that he had not read the feedback. Cognitive conflict occurred though its resolution appeared not to play a role in the learning process. Scaffolding, mainly via the program, suggested that it was the major tool by which participants obtained their objectives. The only episode where cognitive conflict arose was in relation to the destination of protons as a result of photolysis. The additional feedback received by the mixed scoring pair suggested that the protons were transferred from one compartment to another (from stroma to thylakoid lumen in the Light Reaction – Step 2) without a statement as to where they were produced in the Light Reaction – Step 2. This conflict lacked resolution by the program, but intervention by the researcher did so, after debating together about this misconception. This suggested that the feedback opportunities available in the program might not be able to resolve this possible misconception, though on receiving feedback on protons in the stroma they would have undoubtedly targeted the alternative correctly. It was possible

that a misconception of this magnitude could hold serious consequences for a sound understanding of further episodes involving proton flow.

The previous discussion around the activities undertaken by the various participants would suggest that all of them should hold an understanding of the products of the photolysis of water, except for C12 and that they should be able to supply a description to the role of chlorophyll in this process. All participants received feedback at least once on its role. However, their responses in the post-tests failed to support this view. Whilst they all targeted the correct response very confidently in the immediate post-test and most did so (except for C12 who made the wrong choice) in the delayed post-test, there was never any mention of the role of chlorophyll in the initial events of photosynthesis. It was possible that the feedback failed to make clear that chlorophyll carried energised electrons derived from water as the following extract from the program feedback acknowledges.

'....chlorophyll traps packets of solar photons. The energy is used to strip electrons from a water molecule, releasing protons and an atom of oxygen.....the electrons released are transferred along a chain of carriers....'

8.5.4 Task 10

For all pairs, who used the *Photosynthesis Explorer* program the discourse on NADPH was strictly limited. The material on this topic was incorporated into the electron section of the program and came at the end of a lengthy section on electrons, which has already been discussed. The discussion related Task 6 for the high scoring pair suggested that they held some understanding of

membrane structure. On this topic the hypotheses generated by one member (P1) and the feedback responses between this participant and the researcher, suggested an understanding of the events leading up to the synthesis of NADPH. This participant's response to the scaffolding comments implied that there was consistent understanding about the effects of blocking electrons on the synthesis of NADPH. Crucially perhaps the role of protons was mainly applied to synthesis of ATP, though researcher feedback outlined the role of both electrons and protons on the synthesis of reduced co-enzyme. The intrinsic feedback from the practical simulation supported the role of electrons, but not that of the protons. Possibly further clarification of the role of protons and a development of the intrinsic feedback events might have established a greater confidence that both participants understood the events leading up to the synthesis of NADPH. For the mixed pair, since the discourse concentrated on acting on descriptions, there is a strong suggestion that participants would not hold much understanding of this aspect of the light-dependent reaction, even though intrinsic feedback was received and its link to electron flow stated by the researcher with a follow up response by P3.

Researcher: 'So which do you think is directly dependent on electron flow?'

P3: 'NADPH'

It was perhaps unlikely that this or any other participant would hold a big picture of the membrane structure in their minds, especially from the previous discussion about problems with the Mechanisms Window model, since the bridge between intrinsic feedback and theoretical consideration were problematic for a novice. The almost identical pattern of responses shown by the low scoring pair suggested that they would not hold an understanding of this stage of the light-dependent reaction either.

Interactions between the participants were difficult to characterise for these pairs, since the researcher interrupted so much of it. Nevertheless the only pair where there appeared to be marked dissimilarity that might influence the final outcome, was the mixed pair, where the low scoring member P3 made most comments.

Cognitive conflict did not play any overt role in learning. The discourse suggested that there were serious misconceptions and misunderstandings, however, which were potentially serious impediments to understanding, at least for the two of the pairs. These were not resolved.

From the previous discussion, it might be expected that the high scoring pair would demonstrate knowledge about the synthesis of NADPH, since participants, at least P1, demonstrated a consistency of response when making predictions, suggesting an overview of electrons and proton flow from the photolysis of water. For the other pairs, this was likely to be less demonstrable, since predictions were incorrect and there were serious misconceptions. In addition, for these pairs, P3 for the mixed grouping might be expected to perform better because she was mainly involved. Nevertheless it was not expected that any of them would perform particularly well, because there was very little feedback and reflection, other than on the practical simulation. In short, this discussion has suggested that this closed discovery activity using this practical simulation was unsuccessful.

Overall the post-test results conform to this view. There was not a single description that incorporated the role of protons and electrons in the synthesis of NADPH. Whilst a number of choices were correct in the immediate post-test there were a number of anomalies that were not explicable using the variables discussed above. For example, P1, who engaged with much of the discourse made the wrong choice, though only because of the use of the term NADH instead of NADPH. Whilst P2 made the correct one, the program left him with the misconception that NADPH is manufactured in the lumen and transferred to the stroma. In the mixed pair, P3, who was most involved in the discourse, achieved the wrong response. The only participants who performed rather better were those from the pair who scored lower marks overall. Their progress through this aspect of the program was similar to the mixed pair, though their written responses did not refer to the mechanisms of synthesis of reduced co-enzyme, but only to the name of the product.

For the *Cells and Energy* users, one piece of additional feedback was a requirement in order to receive all the necessary information to answer the relevant Task 10 in the Task Booklet. Both the high and mixed scoring pairs received this feedback and apparently reflected on it in order to reach the goals associated with the concepts tested in this task. The high scoring pair did so quite independently of the researcher and very quickly. However, a comment made right at the outset on this section suggested perhaps that one or other or even both of them were seeking answers to the tasks without retaining information in short-term memory. For example, one of the goals was NADP.2H, which when the choice appeared produced the response.

C7: 'That's similar to it, but that doesn't mean anything'

It should have meant something to them because this was a piece of feedback that they had called for in an earlier section. There was a possibility that the expressions of delight in achieving the right answers had more to do with achieving maximum scores than with learning as understanding. On the other hand, one member (C10) of the mixed performing pair appeared to reflect on a previous piece of feedback to target NADP.2H correctly. For the low scoring pair the failure to use feedback previously appeared to cause serious problems in progress on this task. Even when the appropriate piece of additional feedback was called for, subsequent actions required the researcher to tell participants to read it again.

Collaboration profiles appeared to be similar to those in previous tasks with both high and low scoring pairs sharing the discourse and with C10 in the mixed group tending to dominate it.

Discourse analysis suggested that cognitive conflict was not a force for learning for any of these groups and feedback and scaffolding essentially provided through the program enabled two of the pairs to target the goals. However, for the low performing pair two problems, one of which was referred to earlier, were likely to impede further progress. The first of these was the lack of appropriate feedback and the second was prior knowledge. Whilst the first problem could be resolved in the sense that they could easily call for it if required, the second was likely to be insurmountable. The researcher asked participants to read the feedback, but even when they received it there were

conceptual issues related to hydrogen, protons and hydrogen ions, since these were used interchangeably during the discourse.

As a result of this discussion, if scaffolding worked, then the high performing pair should have achieved sound performance in the post-tests, as should the high scoring member of the mixed pair. On the other hand, the last pair should not. The post-tests failed to correlate with the predicted outcome at least for the first two pairs where responses showed no understanding long-term. Only two participants' answers in the immediate post-test suggested a measure of understanding – one from the high scoring pair and the other from the high scoring member of the mixed pair. It is possible to suggest tentative reasons for the differences outlined above on the basis of the operations carried out during the use of this program by participants. First and foremost were the limited feedback opportunities on this topic – one in fact – and second the possibility that the feedback was not read, at least by one member of these pairs. There was certainly some support for this view in the transcript for the high scoring pair. The fact that the high scoring member of the mixed pair performed better than the other member was perhaps linked to the fact that it was this member who targeted the correct answer in the immediate post-test and whose written response could be traced back to an active involvement at a previous stage when answering Question 1, where this participant asked for additional feedback on NADP.2H and immediately knew the correct response.

8.5.5 Task 9

On this task using the Photosynthetic Explorer program discourse suggested that the high scoring pair proceeded in a series of steps reminiscent of that set out by Laurillard, which terminated in reflection on goal-action-feedback events. The low scoring pair appeared to proceed in the same way, though it was uncertain as to whether participants were reflecting on their ideas at the end, though the consistency of their responses suggested that they probably were. The low scoring pair's data suggested that they never reached this stage so that the ultimate goal was not achieved, though P4 read out loud the only piece of program feedback that was available.

For the first time pairs made use of intrinsic feedback and the discourse suggested that they were able to link this to some theoretical material on acidity/alkalinity and proton flow. Interestingly, participants were not expected to make predictions initially, but were able to move from watching the results of a simulation (intrinsic feedback), to linking the effects of light and dark conditions on pH's of the stroma and thylakoid lumen, to theoretical consideration of proton movement and eventually to the synthesis of ATP, with almost all scaffolding provided by the researcher. The discourse events suggested that this strategy of discovery in this closed simulation exercise was successful, though not independently and, as illustrated below when misconceptions are considered, not without risk, because of the persistence of misconceptions, mainly once more about the structure of the thylakoid membrane, but also because of others.

So far as collaboration was concerned, analysis of the results suggested that interchanges were generally consonant and possessed also a great deal of input by the researcher in the scaffolding process. It is suggested that two of the pairs worked constructively towards the goal whereas for the mixed pair, constructive activity was involved, although it only included the researcher and one participant, P4.

The discourse suggested that misconceptions became apparent which, for the high scoring pair developed into conflicting ideas, consequently dispelled through researcher scaffolding. Without it, there was the possibility that participants would not themselves have resolved it or the mechanism of ATP synthesis. For the mixed pair, misconceptions became apparent about the structure of the membrane once more and whilst scaffolding was employed this was never adequately resolved. The problem related to the flow of electrons. The comments of P4 suggested that she did not understand that electrons moved within the membrane, which was three dimensional, so that she assumed that 'punching a hole in it' would assist in the flow of electrons, leading to incorrect predictions about the quantities of high-energy molecules produced, just as it did on topics related to Task 10. This misconception was also apparent for the low scoring pair, once more, but the evidence suggested if the researcher employed a different tack, which was to bypass the problems associated with membrane structure and electron flow and to concentrate on protons instead the goal could most probably have been achieved. Thus a strategic change in emphasis could overcome certain weaknesses in the program.

The results in the Task Booklet correlated well with discourse events. The high scoring pair achieved the correct goal in both post-tests and their descriptions demonstrated a residual, though incomplete understanding of ATP synthesis at a level commensurate with that required at A-level. The low scoring pair also achieved similar results, though were even more confident in the tests. The mixed pair, where goals were not achieved, where misconceptions were not resolved and where the discourse was imbalanced; the partner who played no part in the discourse failed to learn anything. The other member possibly did, though the response was correct for all tests at the same low confidence level. The only suggestion that anything was learnt emanated from the statement in the immediate post-test, which was 'movement is needed by protons', which was included in the segment read out loud.

P3: 'The thylakoid membrane itself is permeable to hydrogen ions. The special ATP synthase complex in the thylakoid allows protons to move from high to low concentration across the membrane and drives the manufacture of ATP'

For the *Cells and Energy* users, there were four goals required in order to achieve sufficient knowledge to secure an understanding for responding to Task 9. The high scoring pair generated a series of feedback / scaffolding and reflection events suggesting the achievement of a sound understanding. Very little of the feedback was derived from the researcher and was only generally supportive rather than providing cognitive assistance. With the second pair a similar approach was suggested by the discourse, though rather more support was required from the researcher. For the low scoring pair, the discourse essentially broke down at one stage, through a lack of conceptual

understanding possibly originating from a deficit of feedback on previous goals. Though the discourse was eventually re-started, the legalistic approach, rather than a logical one using previous knowledge, suggested that the topic would not be understood.

On this section of the program, the collaborative activities, from the very limited evidence, suggested that the discourse for the top scoring pair was shared, though C7 targeted most of the goals. Possibly this suggested a much greater overview of the process of ATP synthesis than the other member. This contention is supported by their differences in confidence expressed in the last segment of additional feedback.

C8: 'I'm just wondering'

C7: 'Yes, it is protons in the thylakoid stroma'

For the mixed pair, the much greater involvement of the high scoring member, especially with the researcher in feedback opportunities suggested a much greater involvement in understanding the mechanism of ATP synthesis by this member. Nevertheless the comment made by C9 right at the very end suggested some participation and perhaps overall understanding.

Researcher: 'So, where did they start' [referring to protons]

C9: They've already built up in the thylakoid lumen, so they moved somewhere else.....the chloroplast stroma'

Finally the low scoring pair shared the discourse, but it was not productive because of the extensive misconceptions, some of which are naïve and others that arose as a result of using the program.

For the high scoring pair cognitive conflict appeared to play no part in realising the task goals. For the other two, cognitive conflict appeared to play a part, as a result of misconceived ideas. It is suggested that in neither case was it supportive of learning, though for the mixed pair it was overcome by scaffolding. For the low scoring pair, cognitive conflict could be suggested as impairing learning, since the task goals were difficult to attain. Nevertheless for this pair, naïve ideas as well as an inappropriate approach and cognitive overload may have led to the difficulties in reaching the goals as discussed below.

The activities of the high scoring pair failed to manifest any cognitive conflict about the location of protons, either in the thylakoid lumen or in the stroma. For the other two pairs, there were undoubtedly problems, which required some researcher intervention for the mixed scoring dyad and rather more for the remaining pair. This problem arose because an answer in a previous part of the program was thylakoid lumen as a destination of protons as a result of photolysis and the current response was also the same. For the first pair, who experienced a problem, one of the pair (C10) reflected on a previous event, by stating that:

‘These were building up in the lumen before, so it must be the stroma’.

After receiving the feedback to the incorrect response, the same participant said:

‘It must be the lumen. Before it didn’t make it clear, did it? It said they already built up in the lumen’.

Scaffolding by the researcher appeared to satisfy one member (C10) as to the reason why this was not so and a much later response showed that the other

member was also satisfied, too. For the low scoring pair, this problem related to the location of protons was not easily resolved. Participants' responses suggested that the space within the thylakoid lumen and in the stroma either were or were not filled with protons as was suggested by C12.

'They're already there, so they're not going to change places'

This was shortly followed by a return to another part of the program on the instruction of the researcher and by feedback from him, as a remediation exercise, but is received no response from either participant. The events that developed from that also lacked any relevance to the foregoing and suggested responses were produced by guesswork.

Results in the post-test correlated very well with the feedback received, the collaborative activities and misconceptions. The balance of the dialogue was weighted towards of one member of each of the first two pairs and they attained the higher levels of understanding. With the low scoring pair, results suggested some understanding, though this can hardly be credited as any more than revealed by the pre-test results.

8.5.6 Anomalies and prior knowledge

A number of anomalies have been suggested in this discussion particularly with regard to the results of one participant, P3, who used the *Photosynthesis Explorer* program and to the results on Task 10 for *Cells and Energy* users. P3 performed less well compared to her partner on all the tasks, except possibly Task 9. Whilst P3 played the dominant role in responding to the researcher's questions and to those of the program, she nevertheless did not perform so well on the tasks. Indeed, the other member allowed her do all the

work without assisting in the scaffolding process at all. One possible explanation for this was prior knowledge, since she performed less well on the pre-A level test than any other member of the selected group as well as in her science GCSEs. Another of course was that the level at which the program approached tasks was outside her ZPD. The anomalous results for Task 10 for *Cells and Energy* users in relation to the low scores on the post-tests for this selected sample (and overall) and the feedback received by all of them are more difficult to explain. Perhaps as noted in the discussion, this originated from there being only a single piece of feedback on this event. Possibly more feedback opportunities would have generated a more positive effect. On the other hand, it could be caused by an unfamiliarity with the co-enzyme concerned, whereas the other chemical product ATP, would have been named as part of the AS course. Yet another possibility was that the Task in the booklet was difficult. This was possible, since the terms PS1 and PS2 were not described in the program and the uses of terms such as oxidation and reduction may well have been unfamiliar at least to some participants. In addition, Task 10 used the name NADPH_2 or $\text{NADPH} + \text{H}^+$ rather than $\text{NADP}\cdot 2\text{H}$ in the program. There was certainly evidence either way on this, since one participant confused NADPH and NADH, though another one recognised that NADPH_2 equalled $\text{NADPH} + \text{H}^+$. Nevertheless the feedback provided them with all other details necessary for the delivery of a positive response.

Prior knowledge may have influenced the outcome of the lower scoring pair (C11 and C12) using the *Cells and Energy* program. Nevertheless as explained in the discussion, their approach to the use of the program was

different in many respects from the other pairs, mainly in that it lacked use of feedback. However, there were a number of instances where naïve concepts were expressed not least in terms of the nature of the thylakoid lumen and stroma.

Whilst there was neither support for an unusual level of ability in terms of their GCSE scores compared with others from the cohort, nor in their overall scores in the pre A-level test, there were concerns about their misconceptions concerning biological compounds and photosynthesis. The evidence from tests suggested that these pairs should be working within their ZPD when using the program, but were the gaps in prior knowledge such that their conceptual understanding of the bigger picture impaired?

8.5.7 Involvement of researcher

Although this aspect was not analysed specifically in Section 8.4 of this Chapter the proportion of time taken with researcher intervention and activity was reported in Section 8.3 for these pairs. Generally *Cells and Energy* users spent a smaller proportion of time in discourse activities with the researcher than the groups employed in the other program. The only exception to this was the low scoring *Cells and Energy* pair. Nevertheless the actual time spent was far, far greater in all the selected cases. It was suggested that this researcher intervention might lead to more comprehensive comments even where there were equivalent confidence ratings in post-test data. The evidence suggested that this was not so. This prolonged discourse, though it might have assisted participants in completing the program, appeared to be

no more effective in providing explanatory comments than the fixed scaffolding opportunities provided by the *Cells and Energy* program.

8.6 Conclusions

- All the selected participants who used *Photosynthesis Explorer* expended prolonged periods at the computer compared with those who used the *Cells and Energy* program. These extended periods failed to deliver over-arching comparative differences in improved levels of knowledge and understanding for these selected participants on the selected questions when compared with the equivalent pairs who used *Cells and Energy* program.
- Whilst there were differences in outcomes on some of the tasks for participants, at each of the three levels, who used different programs, these were generally explicable in the ways that discourse developed during the running of each program – the sharing of it, conflict and its resolution and, not least, the feedback and scaffolding support received on participant activity.
- This discourse, whilst varied, was modulated by the tasks or questions set and, of course, by the program used. Therefore for *Photosynthesis Explorer*, a very much higher proportion of time was spent with no verbal interactions that included working at the keyboard (putting forward hypotheses and predictions in problem solving activities), interpreting instructions on practical simulations, carrying them out and recording results. These events counted for around half the time for this program (>41 minutes).

- However, these silent events rarely included feedback on the results from simulations that explained the causes of the outcomes obtained.
- In contrast, *Cells and Energy* users were not involved in any of these activities save for the occasional keyboard response to the nine questions asked within the program itself.
- For users of the *Cells and Energy* program, periods of non-verbal activity were primarily of two kinds only: either reading (the questions and thinking about their answers) or in receiving program feedback and scaffolding of events in the light-dependent reaction. These feedback / scaffolding activities were prominent features for two of the three pairs (the high and mixed scoring ones) with around one-third of their time (>7 minutes) being spent on this activity.

Feedback / scaffolding was a complex issue, delivered extrinsically largely ad hoc for *Photosynthesis Explorer* in a discovery context and pre-packaged in *Cells and Energy* in a tutorial environment. Only in the *Photosynthesis Explorer* program was feedback provided intrinsically as a result of practical simulations in a discovery approach. Generally the proportion of time spent on extrinsic feedback and scaffolding for *Photosynthesis Explorer* users was very much lower (at least half that of those using *Cells and Energy*) and almost entirely derived from the researcher. Nevertheless the actual time (between 10 and 17 minutes) devoted to extrinsic feedback on the light-dependent reaction of photosynthesis was higher than for users of the *Cells and Energy*

program, though it did not produce a better performance. Indeed, the high and low scoring pairs using the *Photosynthesis Explorer* program, both received around 10 minutes of researcher feedback. So the time spent on this type of feedback was not correlated with performance, though its relative value to the recipients undoubtedly was. Feedback / scaffolding therefore was a complex issue and many factors – such as its type and quality, interruptive events between feedback activities, participants' readiness to receive and act on it, their zones of proximal development, cognitive conflict, prior knowledge and misconceptions - all played a part in its effectiveness. One factor that stood out for *Photosynthesis Explorer* users was the frequency with which a variety of interruptive events occurred with possible detrimental impact on the working memory of learners. Since there tended to be a less complex series of influences affecting learning with the *Cells and Energy* program, conclusions related to it will be considered first. Nevertheless before that there was one important conclusion derived from Laurillard's Discourse model, which was that in order to secure learning about the light-dependent reaction:

- extrinsic feedback was essential and that reflection on it must be focused on cognitive activities that interrogate understanding and not merely previous actions.

The following main conclusions, which answer the questions asked on p. 302, refer specifically to the *Cells and Energy* program.

- Scaffolding, without the need for cognitive conflict did deliver an understanding of events in the light-dependent reaction, which is entirely compliant within a Vygotskian context.

- The construction of this knowledge did occur with appropriate scaffolding material supplied within the program itself, essentially independent of outside assistance, though not for all pairs not least because of inadequate prior knowledge and misconceptions.
- Inappropriate / no use of the rich source of scaffolding material impaired learning.
- Misconceptions generated from the design of the program regarding the location of protons caused real cognitive conflict that could not be resolved for one pair.

One other conclusion for which various explanations were possible may have been based on the extent of feedback.

- The quantity of feedback related to a particular task in the Task Booklet may impinge on understanding. One anomaly, related to the synthesis of reduced co-enzyme, may be explained because of the single piece of feedback, especially when contrasted with the result for the synthesis of ATP.

The following conclusions, which answer the questions posed on p.296, refer specifically to the *Photosynthesis Explorer* program.

- Cognitive conflict provided the springboard for learning relating to one task, which was the source of oxygen. With researcher scaffolding, together with intrinsic feedback from a practical simulation, the program provided an effective means of delivering an understanding of the photolysis of water. Nevertheless this cognitive conflict perspective was no more successful at delivering an understanding of the source of oxygen as when it was not

presented in this way in the *Cells and Energy* program. Cognitive conflict alone was unlikely to have resulted in learning.

- With extensive researcher scaffolding and support, in the context of guided discovery, hypothesis generation and practical simulations, the program was capable of enabling understanding of aspects of the light-dependent reaction [and of the light-dependent reaction overall].
- Practical simulation activities, with intrinsic feedback along with the factual information provided by the program generally failed to achieve knowledge and understanding and largely represented a wasted opportunity.
- Where participants were merely describing changes as a result of manipulating variables and concentrating on surface phenomena without reflection, as particularly demonstrated in the synthesis of reduced co-enzyme, conceptual change was very limited.
- In two specific instances, they were helpful however. In the first, as confirmatory evidence of a prediction about the source of oxygen, where participants had based their prediction using reasoning skills and second, in respect of ATP synthesis, where intrinsic feedback on pH changes could be linked to some physico-chemical principles.
- Misconceptions, which developed as a result of this program in relation to the Mechanisms Window, hindered learning. The opacity of the thylakoid structures and events within them led to a variety of misconceptions, not least the movement of electrons.

Other factors, such as prior knowledge and collaboration, are commented on in the context of both programs in this conclusion section though they are very provisional because of the very limited evidence. With regard to the source of oxygen, many participants were non-committal about its source at the outset and a few considered it as being carbon dioxide. The results suggested that participants were divested of this misconception whichever program was used. Prior knowledge was a particularly complex issue with one pair of participants – the low scoring pair - using the *Cells and Energy* program - whose pre-A level pre-test results suggested confusion about energy. In addition the discourse revealed misconceptions about the physical and chemical nature of the thylakoid lumen and stroma as well as about the differences between protons, hydrogen ions and hydrogen gas. There were undoubtedly problems that ensued from these mistaken views, but they were intermingled with inadequate use of feedback and further misconceptions that developed later, so that it was not possible to separate the importance of prior knowledge from these other variables. Greater certainty may be suggested in this respect for one participant, the low scoring member of the mixed pair, using the *Photosynthesis Explorer* program. Not only had she a lower score than any other of this selected group, but also there was an anomaly regarding her GCSE scores. In the collaborative activities, she took the lead on all the selected tasks, but generally did not perform so well as her partner on all of them, except one. Prior knowledge, might therefore, be considered an important factor in learning. One possible overarching reason for the relatively poor performances of these three participants could be placed within

Vygotsky's concept of zone of proximal development (ZPD). This was particularly relevant to the low scoring participant of the mixed pair whose dominance within the dialogue failed to correlate with understanding in the tasks. Her dialogue rarely went beyond acting on descriptions and her feedback comments generally were comments on simulation exercises. If these observations are linked with naïve ideas on thylakoid membrane structure and prior knowledge, then this anomaly is best explained by suggesting that the program and the instruction were outside her ZPD and therefore beyond her capacity to understand much of the material offered.

Whilst in this research, collaboration was used to reveal participants' activities in terms of Laurillard's Discourse Model, rather than collaborative activities per se. There were a number of insights that revealed the complexity of assigning pairs to the use of computer programs or to any other collaborative endeavour. Reference has already been made to the low scoring member of the mixed pair using *Photosynthesis Explorer*, where she dominated the discourse, but performed less well. The better performing participant was content to let her do all the work, whilst gaining insights into the light-dependent reaction. Nevertheless the question must be asked, would she have performed better with greater commitment, which might have assisted the lower scoring member to realise greater insights also. In contrast, for the mixed pair using the *Cells and Energy* program, the highest scoring participant was dominant, making many of the important decisions. Once more, a similar question must be asked, would the weaker partner have performed better had she been encouraged to be more productive.

The pair whose discourse was most revealing in terms of their thoughts in collaboration with the researcher was the high scoring pair who used *Photosynthesis Explorer*. These really participatory individuals, who were prepared to acknowledge their misconceptions and understanding and to discuss them, appeared to gain most from *Photosynthesis Explorer* from a base that was little different from any other pair.

Finally, *Photosynthesis Explorer* revealed a large number of interruptive events between scaffolding episodes. These interruptions generally continued throughout its use and, as well as simulations of practical activities – in support of hypotheses and predictions – (though not generally conceptual understanding without feedback from the researcher), often included assistance with the program in response to participants' requests. In contrast, researcher interruption was rare in the *Cells and Energy* program (except for the low scoring pair). It can be concluded therefore, that the *Cells and Energy* program – a multimedia tutorial program - could be used by participants working in pairs, with a minimal of assistance, in delivering understanding of facts and principles. However the *Photosynthesis Explorer* program – a multimedia interactive program – could not do so, without additional feedback. The question that needs to be asked at this stage, but cannot be answered in the present study, is could it be made to be more effective, with programmed feedback that would meet participants' needs?

Chapter 9 Conclusions

9.1 Introduction

This final chapter summarises the main achievements of this thesis and the implications that this has for future research, education and for the use of computers in science teaching for the development of conceptual understanding in science subjects.

9.2 Achievements

The research described in this thesis concerns the understanding of the light-dependent reaction of photosynthesis developed by two multimedia programs, *Photosynthesis Explorer* and *Cells and Energy*. The main achievements of this research are:

- Enhanced effectiveness of the tutorial program, *Cells and Energy*, when compared to the simulation program, *Photosynthesis Explorer*, in bringing about understanding of the light-dependent reaction;
- Value of guided discovery as opposed to free discovery in the simulation program, *Photosynthesis Explorer*, in learning about the light-dependent reaction;
- Importance, and nature, of feedback in developing understanding during pedagogic discourse;
- Evidence for general support of the metaphorical tool scaffolding during learning and in the value of working within participants' zones of proximal development in the construction of knowledge;

- Value of pedagogic discourse and interpersonal dialogue between participants and between them and the researcher during construction of knowledge in informing student understanding;
- Value of working within participants' zones of proximal development in the construction of knowledge;
- Variable impact of misconceptions and cognitive conflict on understanding during participant discourse.

Other achievements include:

- Design of two groups of tasks (i) that tests understanding of basic concepts about aspects of photosynthesis that impinge on an understanding of the light-dependent reaction and (ii) that tests an understanding of the light-dependent reaction itself;
- Merit and application of a metacognitive score as an alternative to an ordinal one as a measure of change in knowledge and understanding;
- Guidance offered to teachers when choosing software for the development of student's conceptual understanding;
- Suggestions for support that is required from teachers when students use simulations and tutorial programs.

The initial fieldwork on understanding concepts associated with photosynthesis, particularly the light-dependent reaction, suggested that students after being taught and examined on this topic hold a number of pre-A level misconceptions about photosynthesis as well as on more advanced

topics such as the nature of light, chlorophyll and electron activation, the roles of reduced NADP and ATP, the links between the light-dependent reaction and light-independent reaction, oxidation and reduction, which include physico-chemical ideas as well as those more specifically biological. Previous research has emphasised the negative impact that misconceptions have on student understanding of future topics.

For the Main Study a test was devised that carried two parts: one consisting of pre-A level tasks and the other A-level ones associated with the light-dependent reaction. The tasks were based on the design of Kinchin (Kinchin 2000), which carried an initial statement followed by alternative descriptions associated with the initial one, only one of which was correct. In order to provide a more sensitive instrument to test participants' understanding, they were asked to assign a confidence measure to their choice as well as to describe reasons as to why choices were made. Thus it was possible to provide not only objective and quantifiable measures, but also qualitative ones. These tasks were applied prior to computer use, immediately afterwards and after some delay. The pre-A level tasks suggested that this cohort of students did not hold many, and most frequently none, of the misconceptions identified earlier. The test appeared to be effective in gaining quantitative information, since every participant assigned a value to their choice of statement, and to a lesser extent with qualitative statements, where most described the reasons for the choices made.

In the earlier part of the research, where Pilot trials were conducted with pairs of participants on the simulation program, where no instructions were provided as to how they might use it to find out about the light-dependent reaction, participants became disorientated and scored less on the post-test than they did on the pre-test. Subsequent pairs were told to proceed through the main parts of the program – Explorations and Core Enquiries – in a prescribed way, gaining results that suggested a positive impact on their understanding of the light-dependent reaction.

Participant response could have been awarded a mark on a twelve-point scale, the ordinal score, which had the advantages of including all the quantitative data supplied by participants and enabled the classification of events across the three tests on each of the tasks into four levels described as 'consistent improvement', 'improvement in post test only', 'high consistent' and 'no learning' events. However, this way of measuring participant response carried a number of disadvantages. First it suggested (when the scores were presented graphically) that participants held some knowledge of the light-dependent at the outset (which written evidence suggested that they did not), second it did not reveal an entirely consistent cognitive measure of improvement and finally it was not possible to correlate each score at each stage of the testing process with shades of the qualitative response that accompanied it. The cognitive score carried the potential of removing these disadvantages and was rigorous in assigning a response correct or not, since only if it was 'metacognitively' correct at 60% confidence or above was a task awarded a mark. With such a scoring system it was possible to link a correct

response at this level with a description of the expected task goal and at a lower level with a partially complete written response. It was shown from the statistical perspective that whichever scoring system was used the results were very similar when the overall choices on the tasks were ranked. Finally, when participant quantitative performances were compared by task across the three tests using the two scoring systems, differences between them were minimal. Thus the use of the cognitive scoring system was as valid a technique for determining change as the ordinal one.

Both programs had an effect on participant understanding of the light-dependent reaction – both short and long-term. Both produced significantly increased levels of understanding immediately post computer use and after some delay, though in both of them there were reductions in scores in the long-term. There were no significant differences however between the two programs. Where differences did appear these were on the time spent at the computer. The mean average time spent using the tutorial program was 30.57 minutes whereas for the simulation program this was 90.70 minutes, which was more than three times as long for an apparently similar overall effect on knowledge and understanding. Such a difference has serious implications for the type of program used to confer factual information, knowledge and understanding, especially as there were no significant statistical differences of performances between the two programs.

It was possible to conclude that generally the cognitive scores in the post-test represented a meaningful representation of participants' understanding about the concepts sought for in each of the tasks, since participants comments generally correlated with confidence level afforded to them. Occasionally, though, participants claimed the 'metacognitive' level when this was not justified by the comments made. At the delayed post-test stage this claim was more frequently made; though comments were relevant they failed to meet the target goal expected. At the pre-test stage, the evidence suggested that participants were often likely to claim a highly confident rating to their choices but with associated descriptions that showed no understanding of the light-dependent reaction. Thus there was likely to be an over-inflation of participants' understanding at the outset (particularly where the cognitive scale was used) with consequential diminution of the statistical significance of the changes that occurred as a result of the use of either program.

For the high scoring participants it was possible to conclude that for some of them at least working at the computer with the programs and with the researcher delivered an overall understanding of the light-dependent reaction, since they carried both highly confident correct choices and appropriate descriptions at both the post-test and delayed post-test stages. However, for the *Cells and Energy* program long-term gain by these high scoring participants was less certain than for *Photosynthesis Explorer*, since they explained their highly confident choices in terms that either did not meet the task goal or only partially did so. For the low scoring members, both programs had an impact on their understanding immediately after their use about

specific events of the light-dependent reaction at the post-test stage, but generally not an overarching one, though single events relating to specific tasks were recalled and in some cases remembered long-term. At the delayed post-test stage, little evidence of long-term gain prevailed. For these low scoring pairs at the post-test stage there were more complete explanations linked to choices for those who used the *Photosynthesis Explorer* program than there were for those who employed the *Cells and Energy* program.

There was, therefore overall, from these very limited data, not much evidence to suggest that all the extra time spent (about three times as much) on the simulation program, *Photosynthesis Explorer*, generated much more cognitive gain than the tutorial program, *Cells and Energy*.

The suggested general reasons for this were related to the quantity and frequency of different types of categorised activity undertaken by participants when using the two types of program. Other more specific reasons were those connected with discourse events in terms of continuity (which is related to the quantity and frequency of different activities) and of focus as well as others – the type and quality of feedback and scaffolding, related to participant action on the program themselves. These effects were due largely to the generic differences between the two types of software and are described as program-type orientated.

Other reasons for success or otherwise and possibly irrespective of the program used, best described as personally – orientated, related to the participants' discourse between themselves and the researcher. These included the attitude of the members of a pair at an inter-personal level (co-operative or dominated by one member) and at an intra-personal one, as well as misconceptions and their effects on understanding, cognitive conflict and its resolution and the extent to which extrinsic feedback was used and developed during discourse as well as its quality. In addition, was the feedback and discourse loop matched between participant and researcher talk (or even intrinsic feedback and participant talk) that is discourse that operates within participants' zones of proximal development (at the upper end that is both challenging and progressive), or outside it so that there was little or no blending of conceptual understanding?

A final set of reasons for levels per se, or relative performance on the tasks for the pair of programs could be quality-orientated around the tasks set or the models in the programs themselves. These are best described as design-orientated.

The following conclusions relate to only the selected pairs of participants, though they are covered at some length since they summarise participants' activities whilst using the programs.

So far as the quantity and frequency of the different activities were concerned, participants who used the simulation program spent around half their time without participants' talk (when they were involved in reading instructions or information (or just thinking), formulating hypotheses, manipulating variables in simulation exercises, observing results (both numerical and graphical) and effects on mechanisms window as well using the keyboard to record these events. From the selected pairs, this was never less than 40 minutes and in one case it was 65 minutes. On the other hand, the equivalent silent activities with the tutorial program (reading and answering questions (or just thinking) and looking at animations took a much smaller proportion of their overall time (< 22 per cent), which at most was 5 minutes.

So far as participant talk overall was concerned those who used the tutorial program were spending proportionately more time on it, 19.6 per cent as opposed to 14.3 per cent, but in real time the expenditure was only about one-third of that for the simulations program.

The category that occupied the pairs for the least time was 'participant talk' that primarily occurred between members regardless of the program used. For the tutorial program it was an infrequent event for all pairs, as it was for the simulation program, except for one pair, where the pair experienced problems with practical simulation activities. Nevertheless researcher intervention on matters concerned with the use of both programs captured proportionately more time than participant talk on them. Researcher intervention persisted throughout the simulations program's use whereas for

the tutorial this occurred as instruction at the outset, except for one of the pairs, which experienced misconceptions at an intermediate stage. This, therefore, required part of the program to be rerun. From this evidence alone participants could generally use the tutorial program independently, though not the simulation one.

The other aspect of 'participant talk', that on photosynthesis, was largely taken up by discourse between pairs and overall was the predominant type of talk regardless of the program used. As a proportion of the total time, those who used the tutorial program spent longer on paired discourse (about twice as much), though in real time those that used the simulation program spent longer on it. The mean average was 5.9 minutes for the simulation as opposed to 3.2 minutes for the tutorial.

The total proportion of time spent on 'researcher intervention' was consistently about one-third with the use of the simulation program, whereas for the tutorial it was generally less, except for the pair in which assistance with the program was a feature throughout. The frequency of interventions was less and indeed occurred rarely, except for feedback events on photosynthetic.

The two programs differed markedly in the proportions of time spent on extrinsic feedback that contained information about the light-dependent reaction itself. Whilst those who used the simulation program, received feedback in the form of graphical and numerical data as well as movements (or lack of them) within the mechanisms window during the running of the

simulations, participants were never asked to respond to tasks of a factual nature designed into the program itself. Therefore, any feedback to participants that linked results of simulations to the light-dependent reaction came from the researcher. This was in marked contrast to the tutorial program where feedback was an essential part in the design.

For the tutorial program the proportion of time spent on feedback that provided factual descriptions and explanations of specific events was about one-third of the time spent using the program as a whole. However, the proportion of time was split between feedback provided by the researcher and from the program itself. Around three-quarters came from the program with the other quarter from the researcher. The only anomaly here came from the low scoring pair where the pattern was reversed with researcher feedback dominating. This anomaly was even more profound, since the proportion of time on program feedback was only around one-tenth of the whole operation, whereas the mean average was one-quarter. For the simulation program the researcher provided almost all the factual feedback at around one-eighth of the total activity.

Even though the proportion of time spent on feedback was greater for the tutorial program, the actual mean average time was still greater for the simulation (12.7 minutes) as compared with 8.5 minutes.

The overall pattern of participant – researcher activities when using these two programs were quite different. For the tutorial, they were reading and thinking about the questions set, discussing them together and receiving feedback to their responses mainly from the program but also from the researcher. The focus was on answering questions correctly using the material supplied within the program. On the other hand, for the simulation they were reading and thinking a great deal, though this was mainly on the simulations themselves – creating hypotheses, manipulating variables and observing results – talking between themselves, receiving feedback from the researcher and receiving assistance about the program (on simulations) throughout its use - in other words, a large and varied set of activities.

At a more detailed level, specific discourse between pairs revealed that for the simulations program, discourse focused on the descriptive elements of the results of practical simulations and the problems frequently linked to the correct setting of the variables, rather than the goal set, which related to abstract events of the light-dependent reaction. The researcher offering mappings and assistance with the mechanisms window model of the process also frequently interrupted the discourse. The program offered very little in the way of feedback that clarified or even monitored participants' understanding of events in the light-dependent reaction as a result of their actions. The feedback, though immediate, was almost entirely in the form of both numerical and graphical data, or in the moving parts within the Mechanisms Window. Factual feedback was almost exclusively limited to participation of certain hotspots, such as PS1 and PS2, where the response was limited to a

description. All other feedback was provided by the researcher, which was defined only by the perceived participants' need for it. It was best described as evolutionary, since when it occurred and its descriptive form were both dependent on the environment in which it occurred. These program-orientated features for the simulation program were not effective in delivering efficient understanding of the light-dependent reaction and certainly not in the classroom situation.

On the other hand, the tutorial program users' discourse focused on the task goals, since questions asked demanded answers before progress could be made. The discourse, as already outlined, focused on the light-dependent reaction and was therefore goal orientated. Participants were not deflected by any other activities in the pursuit of these goals as they were with the simulations program. They generally used feedback in order to achieve the task goal. Activation of a specific hotspot always supplied the same feedback, though participants often activated different hotspots in order to target the correct answer. Whilst the verbal discourse focused on photosynthesis, the best interpretation was that its alignment was on success rather than on understanding.

There was evidence in the cognitive walkthroughs that personally-orientated features also played a part in determining success. This research only offers possibilities as to their influence on the learning process. The relationship between sharing discourse and outcomes appeared to be a complex one. There were instances where shared discourse resulted in equivalent results,

but equally in other cases where it did not. Sometimes also a quiet member of a pair achieved better overall understanding of a topic than the individual who dominated the discourse. So at both the inter-personal and intra-personal levels there are complex issues involved. On stronger ground, this research suggested that when descriptions and explanations provided by the researcher / program were within participants' zone of proximal development, then a meaningful discourse developed that resulted in task goals being achieved. When they were not, understanding remained restricted. Cognitive conflict and its resolution as well as misconceptions also influenced outcomes.

Cognitive conflict was not in itself the instrument of transforming understanding. So that where a misconception was developed during the use of a program and where this led to disequilibrium, new conceptual understanding was compromised. However, when suitable feedback resolved the conflict, new ideas were accommodated and further progress made. Where prior misconceptions were revealed by the discourse and removed by it, then once more progress was achieved.

The provision of extensive researcher feedback was fundamental to an understanding of the light-dependent reaction with the simulation program. This feedback took various forms from simply affirming participants' results as being correct or not, to descriptions and explanations of events observed in the mechanisms window. The feedback was not always appropriate and sometimes omitted when it could have interrogated participants'

understanding further. With the tutorial program, researcher feedback was useful, though not perhaps always fundamental.

There were design-orientated factors. These were related to the design of the models and simulations (practical or animations) within the programs and the tasks designed to measure participants' understanding of the light-dependent reaction. With the tutorial program, no participant expressed any difficulties with the animations presented as feedback or in the introductory section. However, with the simulations program, participants found the detail of events within the thylakoid membrane difficult to interpret and the researcher difficult to use as a helpful tool in feedback events, especially in relation to protons and electrons involved in the synthesis of reduced co-enzyme and ATP.

The tasks themselves were accessible to all participants, though Task 8 was probably difficult per se and Tasks 3, 5 and 7 problematic for those who used the tutorial program. Task 8 because there were so many variables in the introductory statement – electron transfer, direction of movement and pH changes and an overall muddling of these events. Tasks 3, 5 and 7 carried aspects, such as two different light harvesting units, the energy of different wavelength of light and the Hill reaction, which were all specific to the simulations program. It was not unsurprising, therefore, that the performance on these tasks was rather better with the cohort that used the simulations program.

What then do these contrasting features of participant-program, participant-participant and participant-researcher dialogue, researcher intervention and program use suggest about how tutorial and simulation programs can best be utilised in a scientific domain, such as photosynthesis?

For the tutorial program (*Cells and Energy*), those participants who pursued, either independently or after encouragement, a discourse primarily with the computer but also between themselves in consonant and supportive ways at the stages outlined in Laurillard's Discourse Model achieved successful outcomes. Where this did not occur and where considerable researcher intervention was required there was only very limited understanding of the photosynthetic process. The researcher dominated the discourse here and participant responses were brief, demonstrating limited conceptual understanding overall and of the assistance provided. Where discourse was shared between participants and where feedback and reflection related to successful responses, sound knowledge by both participants was achieved, where it was not the dominant member gained most. Nevertheless silence was the predominant activity (taking up about two-thirds of the time for the most successful pairing), but this was very much involved with answering tasks and with extrinsic feedback events, which took place almost exclusively on the light-dependent reaction section of the program.

For the simulation software (*Photosynthesis Explorer*), free discovery (from the Pilot Study) was not a sound pedagogical approach to learning with this program and even where discovery was more guided in the Main Study, there

was a lot of researcher input. The extra researcher activities, which included explaining the model, providing extrinsic feedback to the simulations, were extensive and what is more lengthened the sessions by almost an hour. This finding suggests inefficient use of time and it would not be possible for a classroom teacher to spend this much time with each pupil during a lesson. The dialogue between pairs themselves rarely focused on the development of an understanding of the light-dependent reaction itself, but rather on intrinsic feedback from the simulations. This seriously impaired progress and diverted attention away from photosynthetic events to the results of simulations without an accompanying dialogue on and understanding of the light-dependent reaction. The time spent in silence, which accounted for 50% of participant time (about 45 minutes out of a total 90-minute activity), was occupied not on extrinsic feedback, as in the *Cells and Energy* program, but on reading and thinking about the simulations to be done, hypotheses to be formulated and the conclusions to be reached about the effects of manipulating variables – none of which was supported by feedback on the critical features of these events. This failed to scaffold participants towards an understanding of the light-dependent reaction, without the feedback provided by the researcher. In contrast, to the *Cells and Energy* program teacher intervention was a necessity if understanding was to be realised.

As with the *Cells and Energy* program, consonant and most importantly shared dialogue between members of a pair realised successful outcomes. However, in the case of *Photosynthesis Explorer* users this only happened where the researcher was also heavily involved in consonant and rich

exchanges. Where consonant exchanges also featured, as with the low scoring pair, these were largely in agreement with the researcher's comments, added little to the ongoing dialogue and demonstrated little of the members' understanding or lack of it. Where collaboration was not shared, equivalence was not achieved, but in contrast to users of the *Cells and Energy* program, the silent member of the pair gained greater understanding. This was considered to be anomalous and illustrates perhaps the complexity and the variables of the collaborative enterprise and more importantly calls for further research.

This question of the balance between participants – whether they are learners or facilitators in the collaborative exercise – is an important one for both programs and for computer assisted learning in general. As reported in Pilkington 2004 (p. 161), is it symmetrical/equitable, asymmetric/hierarchical and *'does the tutor both facilitate without dominating and encourage inclusive, 'safe' and constructive participation?'*

9.3 Limitations

Whilst these conclusions are based on a careful analysis of the data, they must be considered with some caution. The main questions are to what extent can these findings be generalised and conclusions predictive?

In one sense because the sample was so small, taken from a selected sample of students, results may not be representative, even for another group of similar background and academic ability. In the same vein, similar results may

not be obtained from students of different academic standing as those from the present study.

In another sense, there is the question of validity of the test tasks themselves in the determination of knowledge and understanding of the light-dependent reaction. As noted in Chapter 5, senior associates from two examination boards validated these tasks.

Third there are differing levels of validity for the conclusions with regard to the data and methods of analysis. Since the statistical analyses were undertaken on the whole sample, these may be treated with more confidence than when sub-sampling was undertaken for discourse analysis, where only six pairs of participants out of forty were used. Nevertheless, many of the findings from the simulation program did support evidence from other researchers and could therefore be considered to be valid. Therefore, findings for the tutorial program should be valid, too.

9.4 Response to the research questions

At the start of this research there were four research questions

1. What are the generic features of photosynthetic software that can support student learning?
2. What are the pedagogical strengths and weaknesses in relation to a pedagogic discourse model, such as that advanced by Laurillard?
3. How can this model inform the construction of a support system to encourage an active teaching strategy in the classroom?

4. How can these findings assist with recommendations for classroom teachers when evaluating and using different pieces of software that can be incorporated into a holistic teaching strategy?

In answer to the first question, the research suggested that a multimedia program, with an essentially tutorial design that contained both descriptive feedback explaining correct responses, together with descriptive comment that explained wrong ones and provided assistance (scaffolding) in understanding possible choices before they were made, could provide most of the support for student understanding of metabolic processes, such as the light-dependent reaction. The multimedia closed practical simulation program on the other hand did not provide an effective learning tool without considerable additional support. Where it was used as an open-ended discovery tool, it failed to deliver knowledge and understanding. Where it was more confined to guided discovery, it was possible to learn about a process, such as the light-dependent reaction, but only with the provision of researcher feedback. Participants' focus was on the manipulation of variables and carrying out the practical simulations rather than on cognitive attention to the underlying causes of the results and as Pilkington & Parker-Jones 1996 (p.1) stated *'...there can be a tendency for students to concentrate on the manipulation of objects, without generating a deeper understanding of the model or principles that lie behind observed behaviour. It seems important to avoid setting tasks which can be completed by attention to surface characteristics without making higher cognitive demands'*.

With regard to the second question, the tutorial program focused student attention on the task goal, which as well as being a strength was also a weakness. The discourse in which participants engaged was one that focused on obtaining the correct answer and was a strength when the highly structured feedback provided them with the necessary factual information in order to realise it, but a weakness when it led to guesswork and reluctance to read the feedback material. On the other hand, the simulation program caused participants to concentrate on practical simulations, manipulating the variables, problem solving and receiving program feedback in the form of graphical and numerical data, so that it lacked focus on the task goal. In addition, the discourse between participants and between them and the researcher lacked the continuity of the 'discourse loop' and often returned to elucidation of the model that required re-description. Consequently the discourse sometimes failed to reach the task goal. Most importantly, the overall time period required to deliver very similar results overall was between two and three times that of the tutorial program.

With regard to the third question, there are a number of observations. Regardless of the program used, the value of working in pairs at the computer is that student discourse informs the teacher of a student's understanding, which may be used as a means of moving the discourse on. Second, since working in pairs makes the construction of individual knowledge during members' interpersonal dialogue partly transparent, it is possible to monitor the progress of each student's knowledge development and offer advice and immediate additional feedback as needed. This requires teachers to develop a

student centred approach to learning with computers. With regard to the either program, there does need to be preparation beforehand in the assignment of pairs and in the assessment of prior knowledge. Nevertheless in a class of twenty-eight or thirty it is at first difficult to envisage how this could be achieved with a simulation program like *Photosynthesis Explorer*. However, for a tutorial program, like *Cells and Energy*, by the use of suitable pairings the problems of multiple questions from students could be minimised and if similar programs were used for different topics during a course the problems would be reduced, from the small number found in this research. With this type of program, the additional discourse support required is at the problem solving stage, since whilst obtaining the right answer is important, a more essential need is to construct a rich discourse (interpersonal as well as interpersonal) in reaching it – students should be allowed either to search for assistance, though prevented from simple guesswork, and expected to make notes on the feedback or have the feedback used available for reference and the number of feedback attempts monitored. In these processes, students would have access to a rich body of factual material that is task specific, and which enhances understanding and recall. The practical simulation program would need considerable additional support in order for students to use it more or less independently and efficiently in obtaining knowledge and understanding. Maybe as Pilkington & Parker-Jones 1996 (p.1) point out '[practical] simulations model the complex ways in which variables interact over time, [and] building a simulation model may be the only way to visualise, and hence gain an understanding of how a system works'. However, even if the design-orientated problems were eliminated from the *Photosynthesis*

Explorer, the omission of appropriate concept-based feedback within the program itself is a fundamental weakness. Nevertheless the program does contain a portfolio file (not used in this research), which made the students' work available for comment, but the feedback would not be immediate. In the research when participants focused on the goals, they were often successful, but this was only achieved through researcher feedback. This absence of appropriate concept-based feedback is a generic weakness associated with simulation programs. Student-centred problems associated with hypothesis generation, observation of results and drawing conclusions are also constraints on successful use of such programs, so that if this program were to be used successfully in the classroom as a starting program for understanding a metabolic process like the light-dependent reaction using a scientific discovery learning approach (SDL), then considerable additional assistance is required. Some recent work by Zhang (2000), Reid et al. (2003) and Zhang (2004) suggest the usefulness of additional support – interpretative support (IS), experimental support (ES) and reflective support (RS), and others have investigated teacher expertise in improving opportunities with simulations (Hennessy et al. 2006) there is, however, a long way to go before a model is found that would enable a closed simulation program to be an effective learning tool in the classroom. Perhaps there is a place for it in terms of remediation as a result of using a program such as a tutorial, where there was a need for students to visualise specific events and develop a personal discourse with the teacher.

In answer to the last question, in a classroom where teachers are experimenting with the adaptation of traditional pedagogical practice to one where ICT is being introduced as a teaching and learning tool, they should be recommended to expend departmental funds on multimedia tutorial programs that scaffold students in the learning process and encourage discourse. Such programs would need to possess interactivity that engages students by providing sufficient concept-based feedback providing for learning and understanding. If such programs also provide visual models of the events described, as with the multimedia tutorial investigated, then understanding would possibly be enhanced further. The findings from this research suggested that a student using this type of program that is structured and scaffolded is unlikely to be presented with problems in achieving each task goal. The main reservations concern the extent and focus of the discourse that precedes it as well as the use of feedback material and another relates to possible misconceptions that might develop and the lack of resolution of cognitive conflict associated with them. Simulation programs would not be recommended as a teaching tool for learning about a metabolic process like photosynthesis, unless there were to be considerable teacher input available on an individual basis even if group work was involved. Nevertheless if discovery learning was considered the acme of conceptual understanding, there would need to be a changed pedagogical approach since, as Osborne and Hennessy (2003, p. 1) observed, there are in science education *'tendencies both to pre-structure investigations and to treat writing [or observing] as a means of recording results rather than forming or evaluating ideas [reflecting on results]. It reflects a culture uneasy with uncertainty and a*

pedagogy correspondingly emphasising coverage of content over development of reasoning' [towards a conceptual understanding].

9.5 Further work

This research suggested that in a very small study a multimedia tutorial program was more efficient at developing an understanding of the light-dependent reaction of photosynthesis. It has enabled certain conclusions to be deduced from the data, but inevitably these are provisional because the study included only forty participants, who were volunteers in the research, were almost exclusively academically able and whose data was sub-sampled at least for part of the analysis. Therefore the first considerations for further work are to:

- analyse data for additional pairs of contrasting participants;
- repeat the present study with a larger sample;
- investigate the effects on participants of differing academic ability.

Whilst the *Cells and Energy* program proved a more effective tool a number of approaches could be used to improve its effectiveness still further. Three possible weaknesses were considered in the conclusions in Chapter 8, which were that Task 10 proved difficult because of the lack of feedback opportunities that, as presently designed, students are likely to be presented with problems as to the location of protons and that some students may tend not to use the feedback appropriately. In these contexts further work that should be considered include:

- comparing the effect of the number of feedback opportunities on learning say about NADP.2H and ATP;

- using a worksheet in conjunction with the program to overcome the problem associated with the 'location of proton' misconception;
- comparing the effects of the program on two groups one with specific instruction about the use of feedback and another without.

Another line of work could include classroom studies. Since this program has been seen to work effectively in a relatively short period of time with a selected group of students. Classroom investigations could be designed which could investigate a number of factors, which might include:

- learning by individuals and in groups;
- learning with and without external scaffolding;
- the effects of prior knowledge on effectiveness.

As extensions, the program could be trialled once more, but using both the light-dependent and light-independent reactions employing similar testing tools as in the present study. Since students may be sensitive to the type of test, it might be useful to set up a comparative and controlled study in which groups of students are exposed either to a traditional, or a multimedia tutorial, method of teaching the light-dependent reaction for a single 40-minute period and then exposing them either to traditional A-level questions, or to a multimedia authoring program using hypertext for measuring external understanding, or to tasks similar to those designed in the present study.

Whilst the multimedia simulation program was also effective at delivering an understanding of the light-dependent reaction, but like the tutorial program, for only a minority of participants, it was not, unlike the tutorial, efficient in doing

so even for this minority of participants, as the program took so long to promote it. This research suggested that one of the major weaknesses was that almost all the feedback available within the program related to data from practical simulations, which were as stated in the conclusions mostly wasted opportunities. The researcher provided all the concept-based feedback in an ad hoc way. Sometimes this was successful and at other times not. As participants were told the values at which to set the variables, outcomes were consistent, so that:

- it might be possible to provide uniform external feedback material in paper form that is resourced from the concepts associated with the light-dependent reaction. Further trials could, therefore, be conducted with groups using either ad hoc external feedback or with this uniform feedback material, as investigated by Veerman's et al. (2000).

Another observation was that in one part of the program concerning the source of oxygen, where practical simulations were used to test hypotheses, cognitive demands were made visible beforehand, with cognitive conflict, scaffolding and practical simulations all contributing to an understanding of photolysis. A further not unrelated observation was that another practical simulation that related to ATP synthesis was linked to pH changes and proton movement, which appeared to be relatively successful. Therefore it should be possible to set up trials with the current program that investigate:

- the effect of some interrogative material, as for photolysis, that require higher-level cognition at the outset before the practical simulations.

Another inhibitory factor, in fact a major one, is the unsuitability of the Mechanisms Window for any interrogation of events going on within the thylakoid. Another piece of further work would therefore consist of:

- the provision of an assistance sheet, which would provide an improved model, similar to the animations in the *Cells and Energy* program or to that in Cheeseman's program.

Failing these, a better approach would be to design a new simulations program, if that is possible to do, which:

1. Involves guided discovery, with a pre-determined route for students to follow.
2. Improved design of the animations linked to the light-dependent reaction and the light-independent reaction so that they are equipped for exploration.
3. A control button to inform students when the simulations have been set up incorrectly, so that feedback is related to pre-determined outcomes.
4. A control button that takes students to a feedback loop on their actions, so that they receive immediate feedback on their problem solving activities in terms of the concepts that they should understand as a result of running each practical simulation.

Whilst the previous discussion suggests improvements that can be made to this simulation program to improve its delivery of an understanding of the light-dependent reaction, such as more comprehensive and relevant feedback, there are other issues regarding simulations in which more research is required, in order to further develop their educational potential.

The first strand of future research relates to the notion of additional support, as reported by Zhang (2000), Reid et al. (2003) and Zhang (2004) and outlined earlier in this Chapter. The second concerns the nature of the student discourse be it with the program, other participants or with the facilitator. These are, it is suggested, required to improve a program's delivery of knowledge and understanding of a given domain. The third considers other skills that are developed during the application of simulations, particularly a practical simulation like *Photosynthetic Explorer*. Further work is certainly required to develop greater insights into what additional supports are needed to encourage hypothesis formation, interpretation of results and experimental design as outlined by the above authors. However, what seem to be more important from the current research are answers to the second question. With regard to this, Hartley (1998, p. 250) emphasises that '*user-system interaction engaging in 'deep' processing and explanatory reasoning is necessary if students' beliefs are to undergo revision and development*' and Pilkington (1998) reports on research that encourages dialogue in support of qualitative reasoning. Pilkington (2004) states the importance of the development of discourse and discussion from a Vygotskian perspective, whose ideas are outlined in Chapter 2 (p.18) of this research, which underscores the need for

learners to develop scientific reasoning and conceptual understanding. Whilst there is some research, for example on dialogue during the use of simulations (e.g. Pilkington 1998) there is a need to investigate how dialogue can be managed in practical simulation exercises in order to develop the deep discourse required to bring about conceptual change.

The third question stems from the apparently wasted opportunities during the prolonged periods of silence during the current research when the *Photosynthesis Explorer* program is used. As has already been outlined, there were considerable periods during experimental simulations and after them when participants recorded results, which demonstrated limited focus on the insights that such experiments were meant to promote. However, other skills, such as those of hypothesis formation, observation, graphical interpretation were all being exercised, but not tested. As outlined in Chapter 3, there is considerable research that suggests improvements in such areas where practical simulation programs are employed, but not how these developing skills can be harnessed towards a greater conceptual grasp of a topic. There are therefore four strands of generic further work that spring from this research with regard to simulations. There is a need for additional research into:

- simulation designs that incorporate feedback;
- additional supports for the improvement of interpretive and other experimental skills;
- dialogue/discourse that encourages deep explanation of experimental results as distinct from surface phenomena;

and for research into:

- the holistic effects of improved feedback, experimental skills and dialogue/discourse into the development of an understanding of scientific domains of knowledge.

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Appendix A The present model of photosynthesis

Today there is a picture of the photosynthetic process as consisting of

1. The light-dependent reaction, and
2. The light-independent reaction.

Both reactions occur within particular organs of green plants, usually leaves, inside cell organelles, known as chloroplasts (Figure 1), which are surrounded by double membranes. Inside they are compartmentalised by membranes, so that there is essentially a system of membranous sacs called thylakoids, which contain chlorophyll and a chain of carrier molecules for the movement of electrons. Often the thylakoids are stacked so that structures called grana are produced. The space inside the thylakoids is called the lumen. The rest of the chloroplast consists of a structure less matrix, called the stroma, which contains various enzymes. The light-dependent reaction occurs in the thylakoids and the light-independent reaction in the stroma.

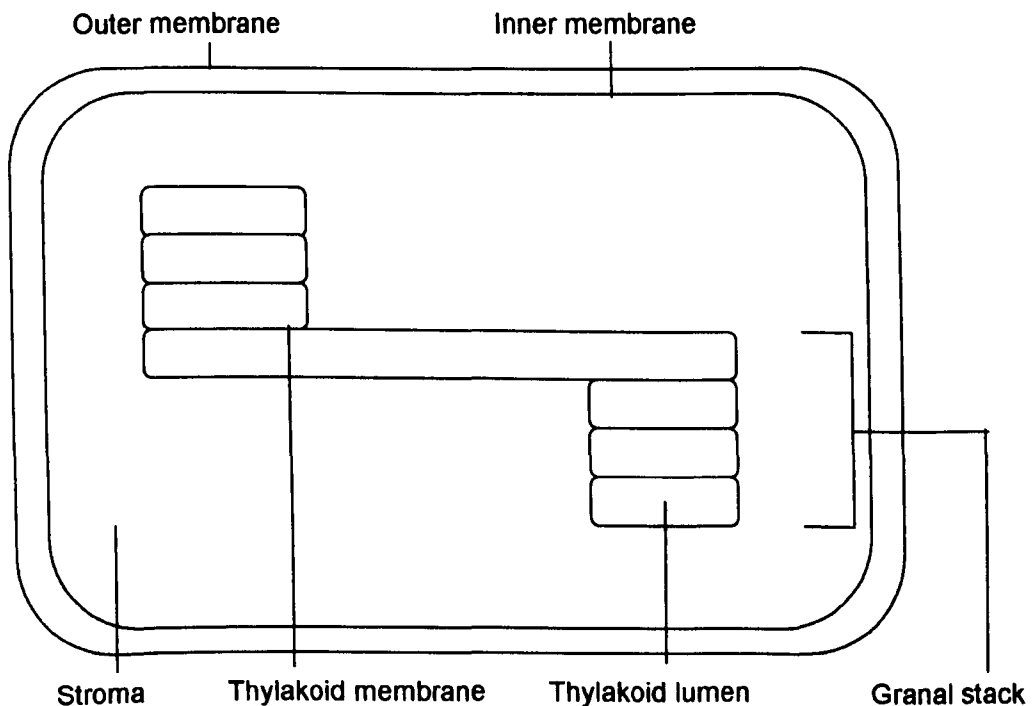


Figure 1 Chloroplast structure

In the light-dependent reaction, oxygen is released by the photolysis of water, and adenosine triphosphate (ATP) and reduced nicotinamide adenine dinucleotide phosphate (NADPH) produced for use in the light-independent reaction.

In the light-dependent reaction, light energy (1) energises electrons in chlorophyll (PSII) producing a strong reductant Q, which can then reduce a number of intermediate carriers, such as plastoquinone. Electrons are lost from chlorophyll (2) being replaced by those from water, in a process known as photolysis (3). This photolysis also results in the release of oxygen (4) and protons. The energy lost by electrons is used to drive protons from the stroma to the lumen of the thylakoids (5), hereby creating a proton gradient, which is utilised by an ATPase in converting ADP to ATP (6). Additional energy is delivered to electrons in photosystem I (PSI), which are used to synthesise reduced NADP (7). These events are summarised in Figure 2 and in further detail in Figure 3. The light-independent reaction, which occurs in the stroma, uses the reduced ATP and reduced NADP in producing carbohydrate. Ribulose bisphosphate, a five carbon, sugar is carboxylated using carbon dioxide with the assistance of the enzyme RUBISCO (8), resulting in two molecules of glycerate phosphate. This is reduced to glyceraldehyde phosphate using ATP and reduced NADP from the light-dependent reaction (9), concerting them back to ADP and NADP⁺ (10). Some of the glyceraldehyde phosphate is used to produce organic product (11) whilst the rest is cycled back to form ribulose bisphosphate (12).

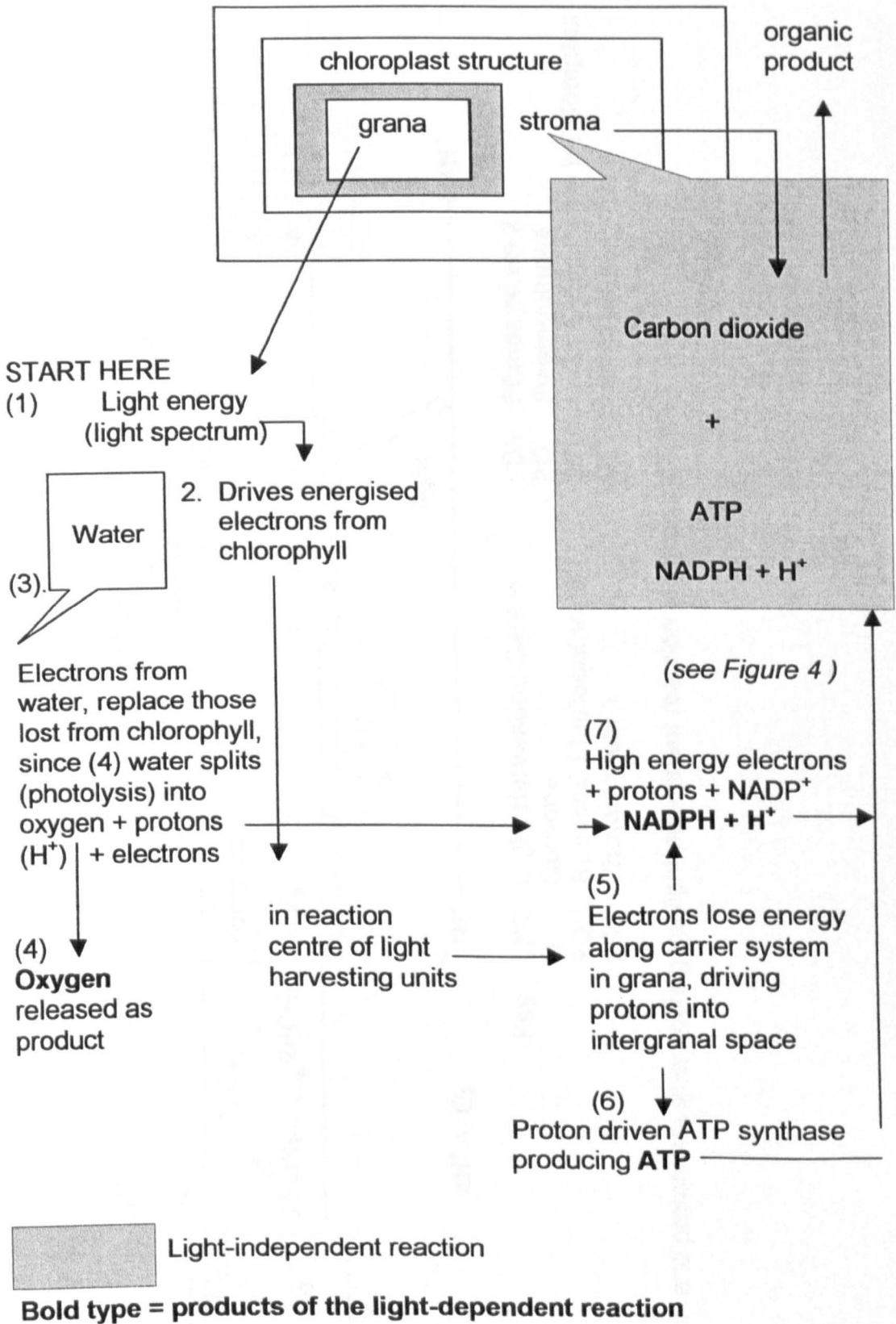
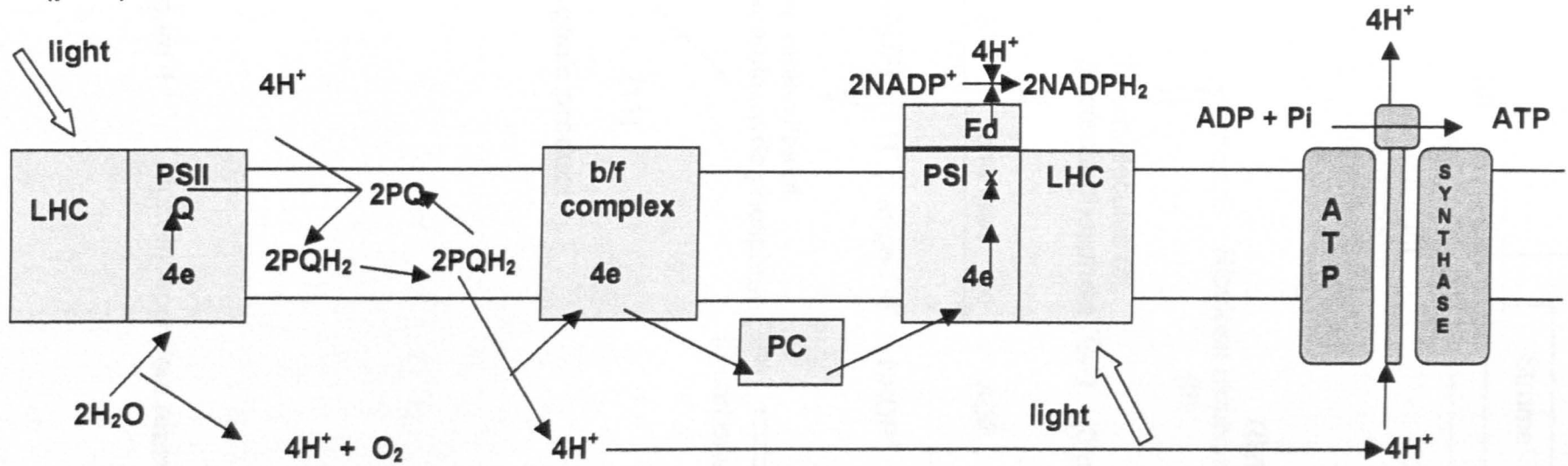


Figure 2 Light-dependent reaction of photosynthesis

Stroma (pH 8)



Lumen (pH 5)

Key	LHC	Light Harvesting Centre	PSII	Photosystem 2
	Q	Quinone	PQ	Plastoquinone
	PQH ₂	Reduced Plastoquinone	b/f complex	Cytochrome b/f Complex
	PSI	Photosystem 1	Fd	Ferredoxin

Figure 3 Electron and proton movement during the light-dependent reaction of photosynthesis

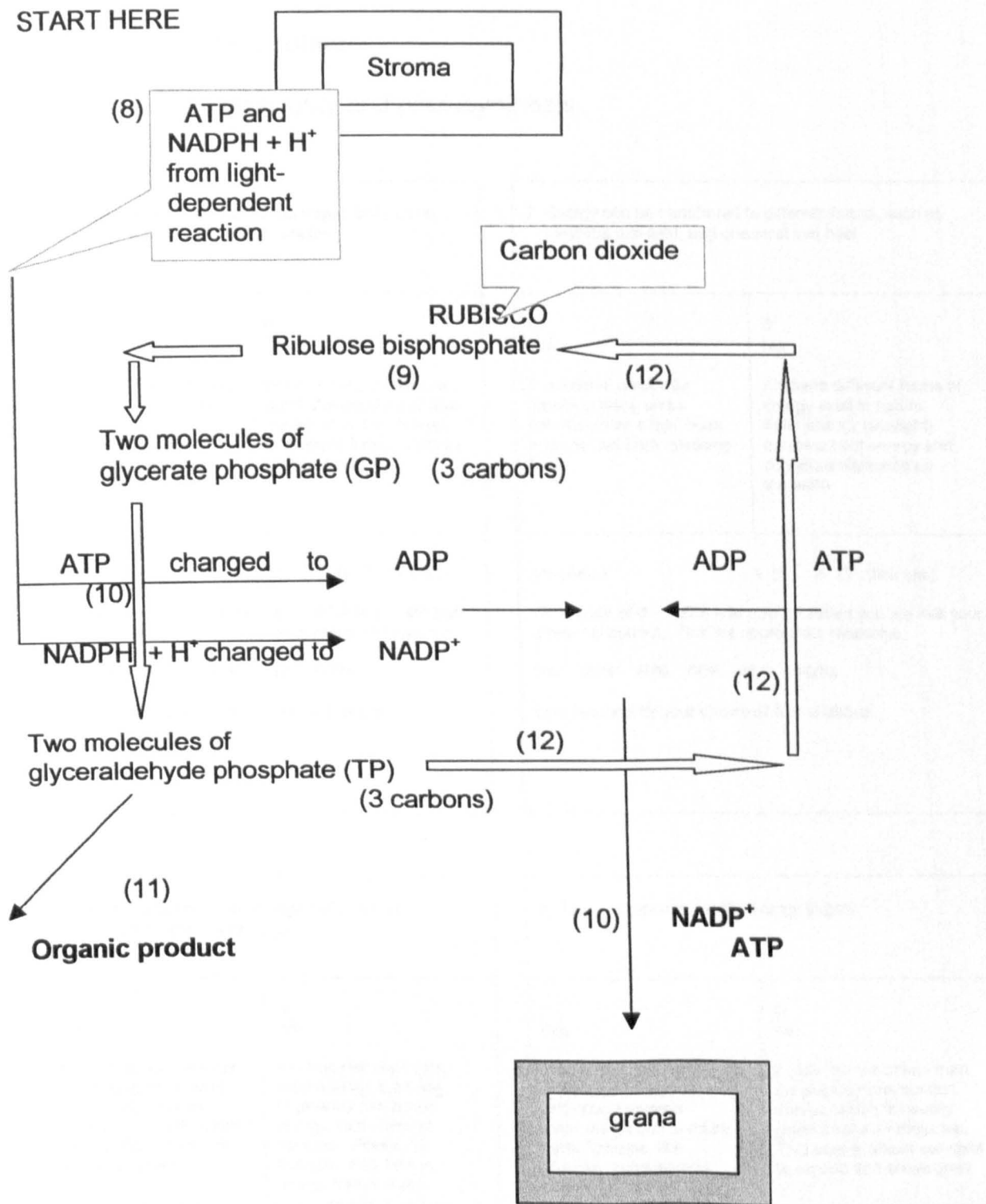


Figure 4 Light-independent reaction of photosynthesis

Appendix B Task booklet

Pre-A level tasks on energy and photosynthesis

1. Energy cannot be created or destroyed, but can be transformed from one form to another	
A No	B Yes
When a match is struck energy is created and this can be transferred to a Bunsen burner to heat up a beaker of water	When a piece of wood is burnt, the energy that was contained in it is released in different forms, such as light and heat
My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)	
On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.	
0% 20% 40% 60% 80% 100%	
Give reasons for your choice of A or B above	

2. Energy can be transferred to different forms, such as electrical into light, and chemical into heat	
A Yes	B No
Currents of electricity travelling along wires can illuminate a light bulb, and coal will burn releasing heat.	All these different forms of energy exist in nature. Solar energy (sunlight) contains heat energy and consequently heats up the earth
My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)	
On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.	
0% 20% 40% 60% 80% 100%	
Give reasons for your choice of A or B above	

3. In living organisms, all energy that they use originated from solar energy	
A Yes	B No
Plants trap solar energy, which is used to make chemicals, such as starch. This is then eaten by animals and provides them with energy	It is true that plants trap solar energy, but living organisms can obtain energy from different sources. Plants, for example, may take in energy from the soil
My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)	
On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.	
0% 20% 40% 60% 80% 100%	
Give reasons for your choice of A or B above	

4. Living organisms require energy to grow	
A Yes	B No
This is true, but living organisms need carbon and other chemical elements as well to make carbohydrates, like glucose, cellulose and starch	Foods that we obtain from the supermarket contain energy, which is usually given a value in kilojoules. This energy allows our cells to expand and so we grow.
My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)	
On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.	
0% 20% 40% 60% 80% 100%	
Give reasons for your choice of A or B above	

5. Photosynthesis produces energy (in the form of starch)	
<p>A No</p> <p>The process of photosynthesis actually uses solar energy (sunlight) in order to produce food (starch) for the plant. Whilst the food that is produced does contain energy, much more energy has been used to produce it. It is a bit like a chocolate bar factory: the chocolate bars that are produced are a source of food energy, but the energy used in the factory (to melt the chocolate, mix it, pour it etc.) is much greater than the energy content of the bars</p>	<p>B Yes</p> <p>Living things need energy. As plants cannot eat in the way that animals do, they have to produce their own energy by photosynthesis. This energy is produced in the form of starch</p>
<p>My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)</p> <p>On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.</p> <p>0% 20% 40% 60% 80% 100%</p> <p>Give reasons for your choice of A or B above</p>	

After Kinchin: Statement 2

6. Photosynthesis converts sunlight into starch	
<p>A No</p> <p>Sunlight is a form of energy whilst starch is a chemical composed of molecules containing carbon, hydrogen and oxygen. It is, therefore, impossible to change one directly into the other because they are made of different things. It would be like trying to convert 'happiness' into peanut butter</p>	<p>B Yes</p> <p>Solar energy (sunlight) is absorbed by chlorophyll that converts it into starch. This can be identified by adding iodine solution, which turns starch black. Large amounts of starch can be obtained from a variety of foods (e.g. wheat and rice) that form the basis of many people's diet.</p>
<p>My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)</p> <p>On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.</p> <p>0% 20% 40% 60% 80% 100%</p> <p>Give reasons for your choice of A or B above</p>	

After Kinchin: Statement 3

7. Chloroplasts trap solar (sunlight) energy	
<p>A Yes</p> <p>Chloroplasts are rather like solar batteries. They change solar energy into a different form (of energy) so that it can be used for energy requiring processes</p>	<p>B Yes</p> <p>Chloroplasts trap certain wavelengths of light especially in the green part of the spectrum, which is why most plants appear to be green</p>
<p>My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)</p> <p>On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.</p> <p>0% 20% 40% 60% 80% 100%</p> <p>Give reasons for your choice of A or B above</p>	

8. Leaf palisade cells are essential to the light trapping process	
<p>A Yes</p> <p>Palisade cells are the only plant cells containing chloroplasts. They are found adjacent to the upper surface of leaves and so are well placed to trap light</p>	<p>B No</p> <p>Palisade cells are valuable, but not essential. Other cells, such as spongy cells and guard cells also have chloroplasts</p>
<p>My choice A <input type="checkbox"/> B <input type="checkbox"/> (tick one)</p> <p>On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.</p> <p>0% 20% 40% 60% 80% 100%</p> <p>Give reasons for your choice of A or B above</p>	

9. When proton channels in the granal membrane are blocked, ATP synthesis stops

<p>A Yes</p> <p>The movement of protons through special channels is essential for ATP synthesis. An enzyme, called ATP synthase, is activated by proton movement, rather like water flowing through a hydro-electric dam</p>	<p>B No</p> <p>The synthesis of ATP occurs during the transfer of electrons in the granal membranes. As the electrons' energy is reduced during transfer from carrier to carrier, ATP is synthesised</p>
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My choice A B (tick one)

On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.

0% 20% 40% 60% 80% 100%

Give reasons for your choice of A or B above

10. Another event in the light-dependent reaction is the addition of electrons and protons to a co-enzyme, thus producing a powerful reducing agent

<p>A Yes</p> <p>This requires two photosystems, PS1 and PS2. PS1 further energises electrons using light energy. Two of these electrons, along with protons produces a strong reducing agent called either NADPH₂ or NADPH + H⁺</p>	<p>B Yes</p> <p>This is essentially correct, but the above description is incomplete. The following gives a more complete picture of the events. Two photosystems are required and nicotineamide adenine dinucleotide is reduced to NADH + H⁺ using electrons and protons</p>
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My choice A B (tick one)

On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.

0% 20% 40% 60% 80% 100%

Give reasons for your choice of A or B above

11. The light-dependent reaction is but one part of of photosynthesis, the other main phase being the light-independent reaction. The light-dependent phase provides materials for the light-independent phase and vice-versa

<p>A Yes</p> <p>The description suggests that these two processes are dependent on each other. The light-dependent phase provides materials for the light-independent phase, which occurs only in the dark</p>	<p>B Yes</p> <p>When a factor needed in the light-independent reaction is in short supply, such as reduced co-enzyme, the rate of the light-independent reaction is slowed down</p>
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My choice A B (tick one)

On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.

0% 20% 40% 60% 80% 100%

Give reasons for your choice of A or B above

12. The light-dependent phase produces only one product, which is oxygen

<p>A No</p> <p>Oxygen is released, but NADPH₂ (also known as NADPH + H⁺) and ATP are made</p>	<p>B Yes</p> <p>Oxygen is the only product. NADPH₂ (also known as NADPH + H⁺) and ATP are not products because they are used again</p>
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My choice A B (tick one)

On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.

0% 20% 40% 60% 80% 100%

Give reasons for your choice of A or B above

13. Products of the light dependent stage are high-energy molecules

<p>A Yes</p> <p>There are three chemicals produced, NADPH₂ (also called NADPH + H⁺), ATP and oxygen, only two of which are high-energy molecules</p>	<p>B Yes</p> <p>There are three chemicals produced NADPH₂ (also called NADPH + H⁺), ATP and oxygen, all of which are high-energy molecules</p>
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My choice A B (tick one)

On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.

0% 20% 40% 60% 80% 100%

Give reasons for your choice of A or B above

14. It is essential that the light-dependent phase occurs, because the oxygen produced is used later on in photosynthesis

<p>A No</p> <p>The oxygen is not used, but is released as a gas. Since the oxygen comes from CO₂ the carbon can now be used to make carbohydrate</p>	<p>B No</p> <p>The oxygen is not used, but released as a gas. The oxygen comes from water. Water splitting is essential because the process makes available electrons for use elsewhere</p>
--	--

My choice A B (tick one)

On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.

0% 20% 40% 60% 80% 100%

Give reasons for your choice of A or B above

15. When considering the overall equation for photosynthesis, the two raw materials are carbon dioxide and water, and the two products are glucose and oxygen. Since the overall equation is:

$$6\text{CO}_2 + 6\text{H}_2\text{O} \rightleftharpoons \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \quad \uparrow$$

the oxygen appears to come from carbon dioxide

<p>A Yes</p> <p>True. It must do so otherwise the equation does not balance</p>	<p>B No</p> <p>False. The equation is very much simplified. The oxygen comes from water</p>
--	--

My choice A B (tick one)

On a scale of 0 – 100% rate how confident you are that your answer is correct. Tick the appropriate response.

0% 20% 40% 60% 80% 100%

Give reasons for your choice of A or B above

Appendix C Written responses to tasks by Participant P2

Q	Pre-test		Post-test		Delayed post-test	
	Res p	Comment	Resp.	Comment	Resp.	Comment
1	X40	There would be a larger surface area for light absorption if it was evenly distributed	✓100	The light is trapped in the thylakoid membrane as this is where the light-dependent reaction takes place	✓80	Chlorophyll is found in condensed patches throughout the plant
2	X40	As chlorophyll is needed the light-dependent reaction can happen anywhere it's present	✓100	The light-dependent reaction takes place in the thylakoid membrane	X40	Light is harvested at the chloroplasts and therefore it is logical that the light-dependent reaction takes place here
3	X20	I guessed	✓80	The two units are the PS1 and PS2	✓60	Just remember that they do
4	✓0	It makes more sense that they are on the inner membrane as the reaction takes place inside the chloroplast	✓40	The light harvesting units are inside the chloroplast on the thylakoid membrane	✓40	The membrane confines the units to one area so the products are easily collected and transported
5	X40	The higher the wavelength the more waves in a set time period and therefore more energy is contacted in that beam	X40	The red light does have a higher wavelength and the infra red burns, unlike UV	X60	The reasons given makes more sense to me
6	✓0	Very unsure, a guess	X60	The electron is needed in the light-dependent part of the chloroplast and splits the water, releasing oxygen	✓80	The loss of the electron means water can split releasing the oxygen, an essential process in the plant
7	✓20	Photosynthesis is one total reaction and cannot be split up into individual parts	✓60	The process of photosynthesis relies on the fact all parts of the reaction occur, each part cannot be split up.	✓40	All aspects of photosynthesis reaction rely on each other
8	X40	The electron movement would cause a proton gradient and therefore movement would occur.	✓80	Protons do not move into the stroma, but instead into the thylakoid membrane via active transport. This reduces the pH of the thylakoid due to the movement of H ⁺ ions present	✓80	The movement causes a lowering in the pH
9	✓60	Due to the difference in pH that would occur if the proton movement was limited the enzymes could no longer work	✓80	ATP synthase is stimulated by a reduction in the pH value in the thylakoid due to more protons	✓100	When the channels are blocked the enzymes are not produced and therefore the correct reactions cannot occur
10	X0	Again unsure	✓40	The two photosystems are in the thylakoid and NADPH is passed from here to the stroma	✓80	NADPH ₂ is produced and is needed as part of the light-independent reaction
11	✓40	The light-independent phase can occur in daytime too, as it is dependent on temperature	✓80	The light-independent reaction does not only occur in the dark	✓100	The light-independent reaction does not only occur in the dark
12	X20	The only product is oxygen, all the other things produced are only half way through their reaction as they are still being used so therefore they are not products	✓100	NADPH and AP are both products which are then used in the stroma for the light-independent reaction	✓100	NADPH ₂ and ATP are produced and needed for the light-independent reaction
13	✓60	Oxygen is not a high energy molecule	✓100	Both ATP and NADPH are high energy molecules and pass into the stroma for the light-independent reaction	✓80	Oxygen is not a high energy molecule
14	X60	The oxygen is released and the carbon which stays must be used and therefore carbohydrates are made	✓100	The oxygen cannot come from the carbon dioxide as this is used in the production of sugar	✓100	The oxygen from the carbon dioxide is needed for the formation of sugars
15	x100	The equation cannot balance if it comes from water as water has merely O whereas the oxygen is O₂	✓100	The oxygen comes from the water as the carbon dioxide is used for sugars. The equation can be balanced if 12 molecules of each one are used	✓100	The equation is over-simplified, the oxygen comes from the water as the oxygen in the carbon dioxide is needed for sugar formation

Table 1 Responses of Participant P2 (7B) to pre-test, post-test and delayed post-test tasks Key: heavy shading = high confidence/ goal concept equivalent; light shading = low confidence / partial goal concept; no shading = wrong response / no understanding; bold type = misconception

Appendix D Sample tables of the percentage time spent on different activities

Section	Topic	Percentage time on each participant pair activity										Percentage time on researcher activity				Percentage of time spent on Researcher + Participant activity
		Silence				Talk on program			Talk on photosynthesis			Intervention				
		Working at keyboard	Manipulating the simulations	Feedback on practical simulations as data + changes in Mechanisms Window	Reading	Between each other	Asking questions	Response to researcher	Between members	Asking questions	Response to researcher	Instruction on photosynthesis	Assistance with program	Asking questions	Providing feedback / eliciting understanding / scaffolding	
First Look		0.0	1.0	1.9	9.1	0.6	0.2	0.0	0.0	0.0	[0.05]	0.2	4.2	[0.05]	0.1	17.4
Explorations		2.2	0.2	1.8	4.0	2.7	0.1	[0.05]	0.0	0.0	0.1	1.1	1.0	0.2	1.5	14.9[5]
Core Enquiries	Reactants + Products	0.8	0.1	0.1	1.5	0.1	0.5	0.0	2.1	0.1	0.0	2.2	0.0	0.0	2.8	10.1
	Light + Photosynthesis	1.2	0.4	1.4	2.2	0.2	[0.05]	0.0	0.4	0.0	0.6	0.0	0.5	0.7	0.7	8.3[5]
	Photosynthetic reactions	1.4	0.3	0.9	3.0	1.2	[0.05]	0.0	0.1	[0.05]	0.2	0.0	1.6	0.6	1.2	10.6
	Energy storage compounds	1.9	0.4	2.4	3.8	0.5	[0.05]	[0.05]	2.5	0.4	0.5	0.5	0.2	0.2	2.4	15.8
	Electrons	0.3	0.3	0.5	3.0	0.8	0.1	0.0	0.7	0.1	0.3	3.3	0.8	1.6	1.3	13.1
	Protons	1.5	0.2	0.5	1.4	0.0	0.0	0.0	0.0	0.0	1.3	1.0	0.7	1.1	2.0	9.7
Percentage time spent on participant / researcher activity		9.1	2.9	9.5	28.0	6.1	1.0[5]	0.1	5.8	0.6[5]	3.0[5]	8.3	9.0	4.4[5]	12.0	
		49.5				7.2[5]			9.5			33.7[5]				

Table 2 Percentage time spent on different activities by Pair PE1

Key: Reactants and Products = Source of oxygen Light + Photosynthesis = Thylakoid and stromal reactions Photosynthetic Reactions = Detail of thylakoid and stromal reactions
 Energy storage compounds = ATP and NADPH₂ and inputs and outputs of LDR and LIR Electrons = electron flow and production of O₂, [ATP] and NADPH₂
 Protons = proton flow and the production of O₂, ATP and [NADPH₂]

Appendix E Written responses to Tasks 14 and 15 by Pairs PE1 and CE4

Task No	Program		Pre-test		Post-test		Delayed post-test	
			Resp.	Comment	Resp.	Comment	Resp.	Comment
14	PE	H 7A (P1)	X 20	Photosynthesis requires carbon dioxide, not oxygen. Carbon is needed for organic molecules	✓ 100	The oxygen comes from water	✓ 80	The oxygen comes from water
	PE	H 7B (P2)	X 60	The oxygen is released and the carbon which stays must be used and therefore carbohydrates are made	✓ 100	The oxygen cannot come from carbon dioxide as this is used in the production of sugar	✓ 100	The oxygen from the carbon dioxide is needed for the formation of sugars
	CE	H 8A (C7)	X 60	Both are truish, but C from carbon dioxide does get used to make glucose	✓ 100	Water releases oxygen and also protons and electrons, both of which are used in the synthesis of NADPH + H ⁺ and ATP ⁺	✓ 100	I just remember this too
	CE	H 8B (C8)	✓ 40	Electrons can then be used elsewhere	✓ 100	The water is split forming oxygen, which is a waste material from the plant. The splitting of water makes the protons and electrons used elsewhere and oxygen is a product – the process is therefore essential	✓ 100	The water is split, which produces electrons to make NADPH + H ⁺ which is essential. The oxygen is made from splitting the water and is released as a gas / product of photosynthesis**
15	PE	H 7A (P1)	✓ 40	The equation could balance wherever it [oxygen] comes from	✓ 100	The oxygen does indeed come from water	✓ 80	The oxygen comes from water
	PE	H 7B (P2)	X 100	The equation cannot balance if it comes from water as water has merely O whereas the oxygen is O₂	✓ 100	The oxygen comes from the water as the carbon dioxide is used for sugars. The equation can be balanced if 12 molecules of each are used***	✓ 100	The equation is over-simplified, the oxygen comes from the water as the oxygen in the carbon dioxide is needed for sugar formation
	CE	H 8A (C7)	✓ 80	The given equation neglects to mention many more complex processes	✓ 100	The oxygen is released in the oxidation of water	✓ 100	Remembered this too, and after all that. I just know it's not as simple as I'd like it to be
	CE	H 8B (C8)	X40	Chemical equations must be balanced	✓ 100	The equation is an overall equation, which is simplified. The oxygen is produced from the water, which also produced protons and electrons, which are essential for the reaction. The above equation is simplified so that an ionic equation is not written	✓ 100	The equation above is balanced but simplified as the water is split producing electrons to make the NADPH + H ⁺ and the oxygen as a result of water splitting. The equation is very much simplified

Table 4 Responses of high scoring pairs PE1 and CE4 on Tasks 14 and 15 on pre-, post- and delayed post-test

Key: heavy shading = high confidence / goal concept equivalent; light shading = low confidence / partial goal concept; no shading = wrong response

TASK 14 = OXYGEN AS A PRODUCT THAT IS NOT USED ELSEWHERE

TASK 15 = THE OVERALL EQUATION