International Journal of Artificial Intelligence in Education, (1999), 10, 198-220

Ecolab: The Development and Evaluation of a Vygotskian Design Framework

Rosemary Luckin and **Benedict du Boulay,** *School of Cognitive & Computing Sciences University of Sussex Brighton BN1 9QH UK*

Abstract. The Zone of Proximal Development is an appealing and persuasive idea for those concerned with how best to help learners learn. In essence the ZPD requires collaboration or assistance for a learner from another more able partner. The need for this more able learning partner arises from the belief that the activities which form a part of the child's education must be beyond the range of her independent ability. The learning partner must provide appropriately challenging activities and the right quantity and quality of assistance. Teachers are able to fulfil the sort of collaborative partnership role required by the ZPD; the Vygotskian inspired design framework presented here explores the ways in which computers may be able to do likewise.

The Ecolab is an implementation of the Vygotskian design framework. It is an interactive learning environment which helps children aged 10 and 11 years to learn about food webs and chains. The Ecolab provides a flexible environment which can be viewed from different perspectives and run in different modes and in increasingly complex phases. There are adjustable activities to be completed and assistance is available from the system. The elements of adjustable assistance available to the system comprise the Zone of Available Assistance (ZAA) applicable to that system. The elements of this ZAA which meet the needs of a particular learner at a particular moment in time comprise the Zone of Proximal Adjustment (ZPA) which the system needs to make for that learner. Three approaches to the construction of this ZPA have been implemented and evaluated within the Ecolab. This evaluation demonstrates the efficacy of the design framework and illustrates that different styles of interaction and collaboration can be supported within an interactive learning environment.

INTRODUCTION

This paper suggests an approach to educational software design which builds upon the notion of software scaffolding (Soloway, Jackson, Klein, Quintana, Reed, Spitulnik, Stratford, Studer, Eng, & Scala, 1996; Wood, Bruner, & Ross, 1976) through the work of Vygotsky on the Zone of Proximal Development (ZPD) (Vygotsky, 1978; Vygotsky, 1986; Vygotsky, 1987). The idea of using theory to inform design is not new, systems such as those of Tennyson, Christensen and Park (1984), Chan, Lin, Lin and Koo (1993) and Anderson (Anderson, 1976; Anderson, 1984; Anderson, Corbett, Koedinger, & Pelletier, 1995; Koedinger, Anderson, Hadley, & Mark, 1997, for example) have used a cognitive learning theory as the basis of the instructional theory which is implemented in their computer systems. Cognitive models can provide the principles upon which the software can be built and in return the software provides a testbed for the cognitive theory (Anderson, 1984). Likewise, the scaffolding metaphor is not a recent construct, it was first introduced by Wood, Bruner and Ross (1976) to describe the process by which effective teachers assist students to bridge the gap between independent ability and collaborative capability i.e. the ZPD. It was originally applied to face-to-face tutoring situations, but has also been successfully adapted to a variety of instructional settings in which computer software provides scaffolding support. Learner Centred Design (LCD), for example, offers a software design framework which advocates learning supports in the form of scaffolding as its central tenet (Soloway et al., 1996). A range of different approaches to scaffolding have been implemented, including systems designed for single learners (Wood, Shadbolt, Reichgelt, Wood, & Paskiewitz, 1992) and to support collaboration amongst groups of learners (Guzdial, Kolodner, Hmelo, Narayanan, Carlson, Rappin, Hubscher, Turns, & Newstetter, 1996). The novel perspective of the work described in this paper arises from the combination of the particular theoretical foundation and software scaffolding. Through reviewing and reflecting upon the theory behind the ZPD, a system of software scaffolding which dynamically adapts to the individual learner's collaborative capability has been developed. The focus of this adaptation is to ensure that the learner is extended beyond what she can achieve alone.

Attention to Soviet psychology, and in particular the work of Vygotsky, offers a philosophy which is directed towards the nature of the relationship between a child's educational activity and her subsequent development. Both the teaching and learning processes are encompassed within the Russian term 'obuchenie' which is used by Vygotsky and which is often translated as 'instruction'. The inseparability of these two processes is then highlighted through the emphasis which Vygotsky places upon interaction between a learner and her environment. The development of the individual is the result of her internalisation of this interaction. The extent to which the way that a child is taught, or rather the way that she experiences education, can influence this internalisation and subsequent development is of interest here. Vygotsky addressed this issue through his investigation of the relationship between development and learning. This relationship was the object of his attention when he proposed the Zone of Proximal Development as the essential 'ingredient' in effective instruction (Vygotsky, 1986). He defined it as: "The discrepancy between a child's actual mental age and the level he reaches in solving problems with assistance" (Vygotsky, 1986). However, there are two aspects to the ZPD which need to be recognised. First, it is a measure of the child's potential ability (Vygotsky, 1986), and second it is something which must be created by the interactions within the child's learning experience (Vygotsky, 1987).

A fundamentally important feature of the ZPD from either aspect is the necessity for collaboration or assistance from another more able partner. The need for this more able learning partner arises from the belief that the activities which form a part of the child's education must be beyond the range of her independent ability. Within a Vygotskian paradigm effective instruction involves the teacher (or more able peer) acting as a partner, enabling the child in her pursuit of success. This requires the provision of appropriately challenging activities and the right quantity and quality of assistance. The learner can then be inducted into the culture of her society and empowered as an autonomous learner (Becker and Varelas, 1995). Teachers are able to fulfil the sort of collaborative partnership role envisaged within this theory. This paper explores the ways in which computers may be able to do likewise.

The Ecolab software is initially described in overview. This was used to define three different systems for the purpose of comparative evaluation. The knowledge representation which defines the structure of the learning environment and which is common to all three variations of the Ecolab is then described in detail, as are the variations of collaborative support which each system provides, the method adopted for modelling the user, and the features which differentiate the three systems. The results of the evaluation study conducted with the Ecolab are explored to consider the design improvements which they suggest.

SOFTWARE DESIGN FRAMEWORK: THEORETICAL FOUNDATIONS

The ZPD concept needs clarification in order to crystallise its interpretation into a form which permits the operationalisation necessary for the construction of a design framework. Two additional constructs: The Zone of Available Assistance (ZAA) and the Zone of Proximal Adjustment (ZPA) are introduced in an attempt to clarify the interpretation of the ZPD which is being used within the Ecolab (Luckin, 1998). The framework developed here, and used in the Ecolab, is concerned with the implementation of a system which can interact with respect to the ZPD of a single user. It is not suggested that this is the only way of viewing the ZPD concept's application to software design, merely that it is *one* way to use the concept.

The assistance provided by a more able learning partner needs to pay attention to the nature of the activity which is offered to the child and to the help which is made available to her as she attempts to complete this activity. Any adjustment to either the activity, or more precisely the learner's role in the activity, or the help she is offered needs to be in line with the system's beliefs about the child's ZPD. The activity must not exclude strenuous mental effort on the part of the child, but it must be possible for her to achieve success with some help from the system. The learning experience may well be hard work for teacher and learner (Adey, 1996).

The ZAA describes the variety of qualities and quantities of assistance which need to be available to enable the more able partner (whether human or computer) to offer appropriate assistance to the child. Part of the aim of human and computer learning partners must be to maximise the variety of assistance which can be made available. A system or teacher with a large ZAA has the potential, in principle, to deal with a wide variety of learners: it has the basic capabilities that could be applied. However, the assistance which is selected and actually offered to the child needs to be matched to that particular child's ZPD. This is where the Zone of Proximal Adjustment (Murphey, 1996) comes into play. The ZPA represents a selection from the ZAA appropriate for the given educational situation. Clearly, if the ZAA is impoverished then this will limit the possibilities for the ZPA. Moreover, even if the ZAA is versatile, an inappropriate selection of ZPA can be made. So the aim for the software designer becomes that of maximising the ZAA and providing a means of targeting the ZPA so that it is as close as possible to the child's ZPD. The goal is to assess the child's ZPD and then adjust the system to take account of this assessment. The ZAA and ZPA are used in the evaluation of the system's use in addition to offering a way of explaining the interpretations of the collaborative learning relationship embodied within the Ecolab project.

THE ECOLAB SOFTWARE

Interacting with the Ecolab

The metaphor underlying the presentation of the Ecolab to the child is that of an Ecology Laboratory. The Ecolab is an environment into which the child can place different organisms and with which she can explore the relationships which exist between them. The overall motivation which is presented to her is that she should explore which sort of organisms can live together and form a food web.

The Ecolab operates in two modes: *build* and *run* and is controlled by the child's mouse driven commands. *Build* mode allows the child to construct her mini world of plants and animals by adding those of her choice. When switched to *run* mode she can activate these organisms. There are three activation options: First, individual actions can be specified and then observed in *step* mode. For example, the child can specify that a sparrowhawk will eat a thrush. Second, a series of actions can be specified in *program* mode. This mode allows the child to build up a list of actions for the organisms in her mini ecosystem. When these actions are activated their effect can be observed. If the action specified, either in step mode or in program mode, is possible it will occur and the changes can be observed. If the action is not possible the child will be guided (in accordance with the system variation in use) towards a possible alteration so that the effects of the selected action can be observed. The third and last mode for running does not involve the specification of which individual actions will occur. The particular selection of organisms in the mini-world defines the actions which will take place. In this *free* mode the organisms all behave according to their type.

When a learner interacts with the Ecolab she does not need to deal with the full complexity of possible food web inter-relationships. The learning environment provided by the Ecolab can operate in 4 phases of relationship complexity. This means that not all the possible methods of activating the Ecolab are available all the time. In phase one, which is the simplest, the relationships which can be formed by the Ecolab objects are only those between a food and a feeder: the *eat* or *eaten by* relationship. The second phase of complexity allows the formation of food chains and thus relationships between more than two organisms. The third and fourth phases allow the formation of food webs and relationships between all the different members of the web. The system can switch between these four phases from the less to the more complex, or in reverse from the more to the less complex. The activities available to direct the child's actions are consistent with the phase of complexity at which the Ecolab is currently operating.

Like the complexity of the relationships, the terminology used to identify the organisms can be varied. It can increase or decrease in its generality. For example, whilst initially the child may be working out what happens to the energy level of a *thrush* when it eats a *snail*, as she moves through the activities this may become an *omnivore* eating a *herbivore* or a *secondary consumer* eating a *primary consumer*. Within the levels of generality available, the terminology in use can be varied to be less or more abstract.

In addition to providing the child with the facilities to build, activate and observe a simulated ecological community, the Ecolab also provides the child with small activities of different types. The activities are designed to structure the child's interactions with the system. They provide a goal towards which the child's actions can be directed and vary in the complexity of the relationships which the child is required to investigate. There are, for example, exploration activities which challenge the child to examine the relationships which exist between the organisms she has selected. She might be asked to see how many links she can add to a food web diagram for example. The variations in the complexity of the relationships, the level of abstractness of the description and the type of activity form part of the system's ZAA.

The Interface

In addition to these variations, the Ecolab environment built by the child can be viewed in different ways, each of which emphasises a particular aspect of the relationships which currently exist within the Ecolab. All views have the common features of a menu bar across the top of the screen and a tool bar down the right hand side. This approach was selected because of its consistency with the software packages which the children taking part in the evaluation study had already used. They were familiar with using a mouse to select commands from a menu bar or buttons from a tool bar.

- World view shows a picture of the organisms which are currently members of the Ecolab environment.
- Web view provides a diagrammatic representation of the organisms and the links which exist between them in a manner similar to the food web diagrams used in text books.
- Energy view illustrates each of the live organisms in terms of their current level of energy in a block graph of a type which is consistent with the requirements of the Maths National Curriculum in England and Wales (see Figure 1). The nature of this view does however vary in accordance with the phase of complexity currently in operation. In early phases the child is dealing only with single instances of the organisms selected, whereas in later phases populations of organisms are used.
- History view is a textual description of what has happened in the Ecolab world to date.
- Log view shows the Ecolab logs which summarise all that has happened and the current state of the world.

Within each of these views most of the screen objects will provide the child with information when clicked on with the mouse. For example, clicking on an organism in World view will yield the organism's name, what it eats and what eats it. Which view a child uses is largely, though not completely, under her control. There is also a notebook facility which has simple word processing features and which is always available to the child to enable her to record whatever notes she wishes. With the exception of this notebook facility the child uses the mouse to select commands.

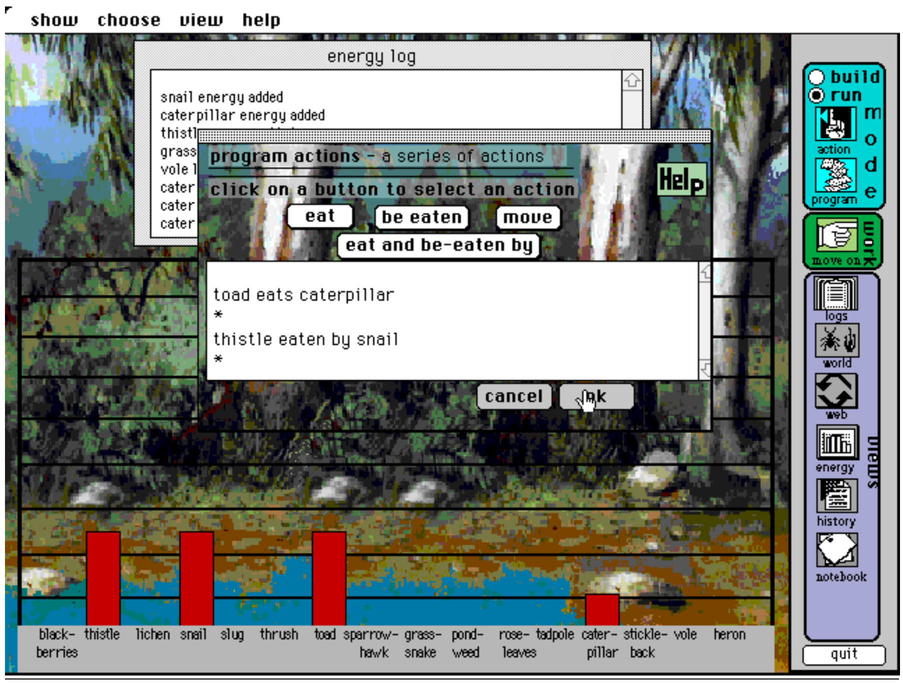

Figure 1. The Ecolab interface in Energy view

DOMAIN KNOWLEDGE REPRESENTATION

The domain knowledge of ecology within the Ecolab is structured in a manner consistent with Vygotsky's view of concepts, as either scientific or everyday (Vygotsky, 1978; Vygotsky, 1986; Vygotsky, 1987). Likewise, Vygotsky believed that concepts could not be studied alone, but must be studied as part of a systematic fabric of concepts. More recent work on teaching and learning concepts (Howard, 1987; Merrill et al, 1992; Rosch, 1988, for example) has also influenced the nature of the knowledge structure. The contact point between the everyday and the scientific is collaboration within the Zone of Proximal Development (Vygotsky, 1986). It is the creation of this contact point that the knowledge base of the Ecolab must facilitate. Attention is paid to the position of concepts within a hierarchical system and to the relationships which exist between concepts at the different levels within this hierarchy.

Knowledge of the subject to be taught must be in a flexible form which is culturally consistent with that of the child if it is to mesh with her already existing knowledge structure (Evans, 1993). The members of an ecological community can be classified into a taxonomic structure which ranges from concepts with which the child is familiar, such as *snail* and *grass*, to those with which she is less familiar, such as *consumer* and *producer*. In addition to understanding the types of concepts which represent the members of the Ecolab community, the child needs to understand the relationships which exist between its different members. These relationships will be the same whether the members are described as *rabbit* and *fox*, *prey* and *predator* or *primary consumer* and *secondary consumer*. Knowledge about the relationships which exist within a food web can be complex, but can be broken down into a structure of composite rules. These rules initially relate to the relationship which exists between individual community members and subsequently to food chains and food webs.

Knowledge representation in the Ecolab can be decomposed into four main elements:

1. Knowledge about Food chains and webs
2. Learning activities
3. Collaborative support

4. Knowledge about the child

Each of these elements allows the realisation of different aspects of the design philosophy.

Knowledge about Food Chains and Webs

Food webs are an important biological concept: they are simplified representations of the feeding relationships which exist in a particular community. An understanding of food webs is central to understanding more complex ecological principles (Alexander, 1982) and knowledge of energy issues is fundamental to gaining insight into global issues such as energy flow and food supply (Lumpe and Staver, 1995). However, biological concepts can be complex and teaching them is deceptively easy (Pedersen and Hallden, 1994). For example, teachers do not perceive food webs as difficult either to teach or learn, but school exam results indicate that learners experience considerable difficulty (Griffiths and Grant, 1985). One cause of the difficulty is that the terminology used varies in its degree of abstraction. Another cause of difficulty is that the relationships in food webs vary in complexity. Some denote a relationship between a pair of individual animals or plants. Others denote more complex relationships, either between triples of individuals or between populations of individuals.

Two dimensions of Food Web Knowledge

There are two connected knowledge structures or dimensions in the system's domain knowledge representation.

- First, the taxonomic hierarchy which describes the concepts making up the members of the community. This forms the vertical dimension of the system's domain knowledge representation.
- Second, the system of rules which the child needs to acquire if she is to understand the relationships which exist between community members. This forms the horizontal dimension of the system's domain knowledge representation.

The resultant links between the different members of the food web community can be divided into two main categories:

L1: *Vertical dimension links:*

These connect concepts within the taxonomic hierarchy in terms of their level of abstraction. For example, specific instances of concepts such as rabbit are linked to the more general concept herbivore which in turn is linked to the concept primary consumer (see Figure 2). It is recognised that the taxonomy may not be entirely based upon the abstraction relationship. However, as the level increases the concepts are those which are less familiar to the child and more inclusive of the subordinate concepts.

L2: *Horizontal dimension links:*

These links connect the nodes which each define a relationship which can exist between concepts (see Figure 3). The relationships within food webs have a rule-like nature which lends itself to a hierarchical style of representation. An example of such a relationship would be an *eat* relationship which could occur between a herbivore and a plant. Within the horizontal dimension of the system's knowledge structure this is referred to as *food-affects-feeder* to emphasise the direction of the energy transfer from food to feeder. The hierarchical structure of relationships is composed in terms of the pedagogic pre-requisite relation between rules, in contrast to the relationship of generality or inclusiveness used in the vertical dimension concept hierarchy. For example, within the food chain:

grass $\Rightarrow$ rabbit $\Rightarrow$ fox the *eat* relationship that exists between rabbit and grass is simpler and needs to be understood before the relationship which exists between grass and fox which are non-adjacent members of the same food chain.

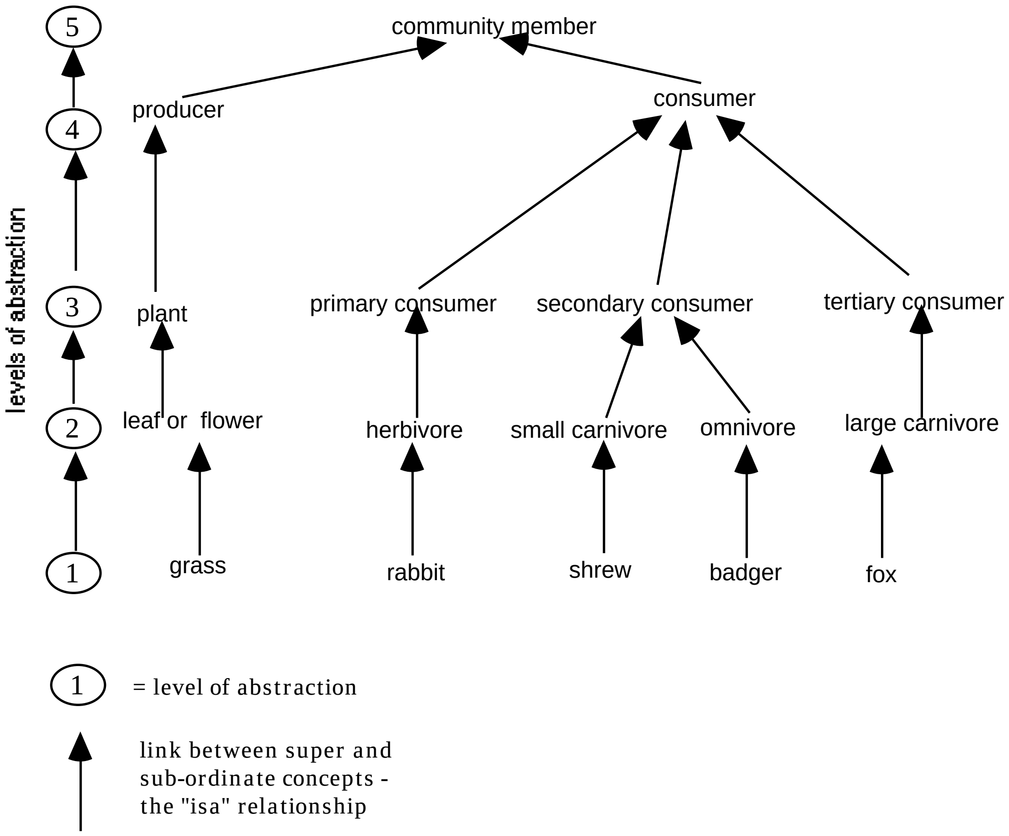

Figure 2. Knowledge Representation: the vertical dimension - taxonomic hierarchy

All the relationships which can exist between organisms in the Ecolab are defined by one of the rules represented by a node in Figure 3. Relationships further up the hierarchy require an understanding of those lower down. Reciprocally, understanding a rule towards the right of the horizontal dimension is difficult without an understanding of the rules towards the left, which are pre-requisites for it. The horizontal hierarchy is divided into four phases. The complexity of the relationship described by the rule node defines the phase (from 1 - 4) to which the node is allocated within this hierarchy. Phase 1 is the simplest and phase 4 the most complex. It is recognised that a certain amount of pedagogical expertise is implicit within this knowledge structure.

The overall organisation into nodes embodying the rules and into phases is adapted from the Genetic Graph (Goldstein, 1982). Examples of the contents of some rule nodes are shown in Table 1. The design of the rule structure within the horizontal dimension of the system's knowledge representation in the Ecolab has been informed by Griffiths and Grant (1985), Lumpe and Staver (1995) and the various science text books generally available for school use. The knowledge included is simplified in some instances to respect the age of the children for whom the system has been designed. In addition, the existence of other factors in the broader picture needs to be acknowledged. For example, the death and birth rates of different populations will be influential in any real community.

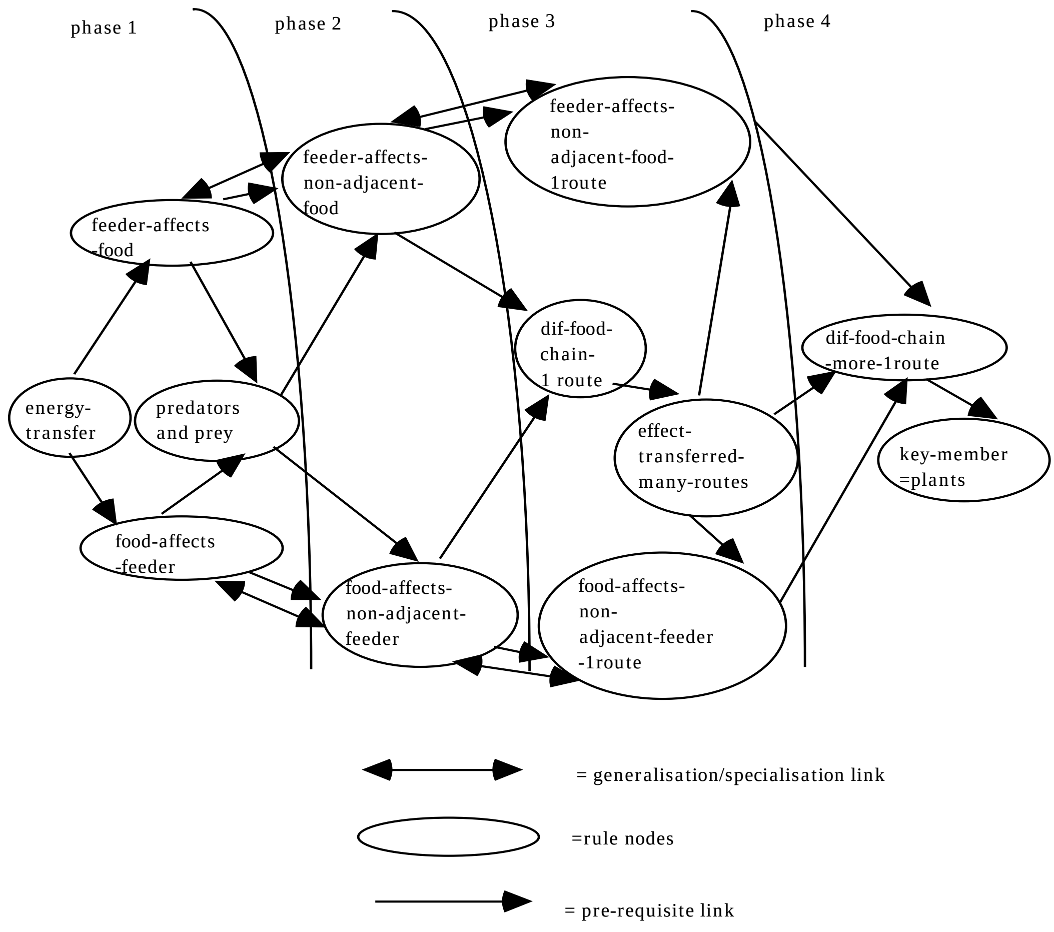

Figure 3. Knowledge Representation; the horizontal dimension - rule nodes

Table 1. Examples of the contents of a rule node from each phase.

Phase of complexity	Rule Nodes	Operation Commands
1	energy- transfer feeder-affects-food predators and prey food-affects-feeder	move be eaten be a predator be prey eat
2	feeder-affects- non-adjacent- food food-affects- non-adjacent- feeder	eat and be-eaten by be-eaten and eat
3	feeder-affects- non- adjacent-food-1route food-affects- non- adjacent-feeder-1route effect- transferred- many-routes	build web remove organism
4	dif-food- chain - 1 route key member = plants	alter size of population produce food

The Relationship between the two dimensions.

It is possible to present all the rules in the horizontal dimension at any of the levels of abstraction in the vertical hierarchy. This means that all, from the simplest to the most complex, feeding relationships can be presented with the participant organisms described by any of the terminology abstraction levels. Potentially, therefore, all nodes in the vertical dimension are linked to all the nodes in the horizontal. For example, the three rule nodes: energy transfer, feeder-affects-food, and food-affects-feeder can apply to the relationship between *grass* and *rabbit*, to the relationship between *leaf* and *herbivore*, to the relationship between *plant* and *primary consumer* and finally to the relationship between *producer* and *consumer.*

Learning Activities

Each of the rules in the horizontal dimension of the knowledge base is associated with one of the commands by which the child activates the organisms in her environment, see Table 1. For example, one of the rules states that a change in the state of a *food organism affects the state of a feeder organism*. The command associated with this rule is the *eat* command. The rule associated with each node can be presented to the child through an activity. A set of activity templates is associated with each rule node. The learning activities provide a goal towards which the child can direct her Ecolab activity. The use of templates for the different types of activity: introduction or exploration, rule definition or combination (part exploration, part rule-definition), ensures that the style of presentation of this content is consistent throughout all nodes. The individual rule node defines the specific content of the activity template: the conditions and operations through which she can achieve this goal will depend upon the organisms she has selected and the approach she adopts. For example, if she is investigating how many links she can add to a food web diagram she may choose to build a program of *eat* commands, but she could satisfy the same goal by building a program from *eat* or *eaten by* commands, or by using a combination of individual *eat* and *eaten by* commands.

Collaborative support

The subject of collaboration represents a large, varied and active area of research within Artificial Intelligence in Education. In this paper the nature of the collaboration envisaged is that between a less able (the child) and more able (the computer) learning partner within a Vygotskian framework. The Ecolab software aims to promote the construction of interactions with the child which create a ZPD with respect to the extent of that child's capability.

Graded help

The Ecolab can assist the child in several ways. Firstly, it can offer graded help specific to the particular situation. There are five levels of help which vary with regard to the quality of the help which they provide. The higher the level of help the greater the control taken by the system and the less scope there is for the child to fail (Wood et al, 1978). At level 5 the system completes the activity for the child. There is no notion of failure in the Ecolab, only variations in the levels of support offered to ensure success. If the level of help offered to the child is insufficient, then the level can be increased (either by the child or the system, depending upon system variation as described later) until the system completes the particular activity for the child. For example, if the child defined the following action: *caterpillar eat thistle* a help dialogue would appear. The text which would appear in the help box as the level of help increases is as follows:

Level 1	Caterpillar does not eat thistle. Try again.
Level 2	Caterpillar does not eat thistle. Try choosing a different food or a different animal feeder - don't forget you can click on different animals and plants to find out more about them.
Level 3	Caterpillar does not eat thistle. There is nothing that caterpillar likes to eat in your world at the moment try adding: rose-leaves
Level 4	That isn't quite right. I'll show you what to choose and you can have another go
Level 5	Thistle isn't the right sort of organism. Let's try rose-leaves

Activity differentiation

In addition to offering the child specific hints to ensure the activity is completed successfully, the difficulty level of the activity itself can be adjusted. This is referred to as *Activity Differentiation*. The term differentiation is used by teachers to indicate a variation in the difficulty of an activity or task so that the same problem can be presented in an appropriate format to learners of varying ability**.** There are three differentiation levels: Level 0 is the most difficult and incorporates none of the differentiation tactics described here. In Level 1 refinement links in the knowledge base are not followed and specific good exemplars are used to direct activity. In Level 2 activities are simplified through partial completion to help reduce the possibility of confusion (Griffiths and Grant, 1985).

The following example of the content of an activity clarifies both the nature of the activity and the sort of collaborative assistance available from the system. Each activity template contains slots into which the details of the activity relevant to the particular node are placed. With 4 types of activity for each of the 12 curriculum nodes there are 48 (4 x 12) activities available. Each of these 48 activities is available at three different levels of differentiation leading to a space of 144 (48 x 3) possible individual activities. In Table 2 the contents of the slots for an exploration template are detailed.

Table 2. Slot contents for an exploration activity template

<table>
<tr><td colspan="3">The Introduction to this rule node provides the following information:
This activity is about predators and prey - we'll find out what the words mean and look at which animals are predators and which are prey.
• Predators are animals which EAT OTHER ANIMALS
• Prey are animals which ARE EATEN by other animals</td></tr>
<tr><td>Differentiation Level 0</td><td>Differentiation Level 1</td><td>Differentiation Level 2</td></tr>
<tr><td>Use the 'action' button to see if you can:
• find out which animals are predators
• find out which animals are prey
• find animals which are sometimes prey and sometimes predators.
• find out which of the animals in the Ecolab are not another animal's prey

Make sure you look at the different views of the world.
Use the notebook to record what you do.
When you have finished click on 'done'.</td><td>Use the 'action' button to explore the following questions:
• The grass-snake is a predator, can you find out which other animals are predators
• The slug is a prey, can you find out which animals are prey
• The toad is a predator to the slug and prey to the grass-snake, can you find any other animals which are sometimes prey and sometimes predators.

Make sure you look at the different views of the world.
Use the notebook to record what you do.
When you have finished click on 'done'.</td><td>Use the 'action' button to explore the following questions:
• The grass-snake is a predator, can you find out which other animals are predators.
• The slug is a prey, can you find out which animals are prey

Make sure you look at the different views of the world.
Use the notebook to record what you do.
When you have finished click on 'done'.
[at his level there is a demo button which the child can use to instruct the system to start the activity for her]</td></tr>
</table>

THREE VARIATIONS ON THE ECOLAB THEME

The Ecolab software consists of 3 variations: the Vygotskian Instructional System (VIS), Woodsian Inspired System (WIS) and No instructional-intervention system (NIS). The aim of the VIS system is the implementation of the theoretical framework already described and is based upon the principle of maximising the system's Zone of Available Assistance (ZAA) and refining the Zone of Proximal Adjustment (ZPA) so that it is in line with each individual child's ZPD. WIS and NIS implement different variations and combinations of the features in the design framework with the purpose of providing a means of evaluating VIS and its design framework. All three systems share the overall educational goal of helping the child understand increasingly complex relationships using increasingly complex terminology. The way in which collaborative support is provided, or rather the ZPA is constructed, varies between VIS, WIS and NIS so that each of them acts as a different type of instructional partner for the child. These are summarised in Table 3. VIS takes the greatest control and *selects* the current node in the curriculum and its degree of abstraction. It also selects the differentiation which will be applied to the activity and the level of help which will initially be offered. WIS offers the child *suggestions* about the type of relationship she should investigate and the type of activity she should tackle. It also sets the initial level of help which will be offered to the child the first time she asks. By contrast, NIS allows the child herself to select the complexity and nature of the task, and the level of system support. NIS can only offer help at levels 1 and 5, thus limiting the choices available to the child to a greater extent than WIS. This offers the possibility of exploring the efficacy of the greater levels of help available in VIS and WIS.

Knowledge about the Child

In order to provide the collaborative support just described the three variations of the Ecolab maintain learner models of differing levels of sophistication. NIS records only the curriculum nodes the child has 'visited'. This record is visible to the child. It makes no decisions for the child and therefore needs no proper learner model. WIS records the curriculum nodes tackled by the child in the same manner as NIS; however, it uses this information to select the suggestions to be made to the child. In addition, it keeps track of the level of help which the child has used so that it can apply a contingent strategy (Wood et al, 1992) to the selection of the next help level. Within VIS, the model of the child is more sophisticated and is a vital system component. In order to achieve the aim of promoting interactions which involve activities that encourage a level of participation appropriate to a particular child's needs, the system must be able to quantify each child's ZPD: which areas of the curriculum are beyond what she can deal with on her own, but within the bounds of what she can deal with successfully when the system provides appropriate support. Within VIS this entails decisions about:

- which nodes in the system's model of the learner are within, or close to being within, her independent ability.
- which nodes in the system's model of the learner are outside her independent ability.
- how much support needs to be provided in order to ensure that the learner is successful when interacting at a node.

In the domain knowledge representation of the Ecolab each node represents an element of the curriculum, something which the child needs to understand: a relationship or a level of terminology abstraction. The learner model within VIS is an overlay of this domain knowledge structure. For each learner a model of this knowledge structure of rule and concept nodes is maintained. However, whereas in the domain knowledge structure an element of the curriculum is associated with each curriculum node (rule or terminology abstraction), in the learner model there are 2 values, referred to as *tags* associated with each node. The first value: the *ability belief tag* is the system's 'belief' about the child's independent ability with respect to this node. The second value: the *collaborative support tag* is a quantitative representation of the amount of collaborative support which the system needs to provide for the child in order to ensure her success with the equivalent node in the knowledge base. These tags allow the modelling of the system's beliefs about which areas of the curriculum are outside the child's independent ability and the extent of the collaborative support required to bring each of these areas within her collaborative capability.

Table 3. Collaborative support within Ecolab

Collaborative Support within Ecolab			
	VIS	**WIS**	**NIS**
Levels of Help Available	5	5	2
Decision about Level of Help made by	system	system and child	child
Levels of Activity Differentiation Available	3	3	3
Decision about type of Activity and Differentiation level made by	system	child - system makes suggestions	child
Extent of Learner Model	Bayesian Belief Network (BBN) of values representing the system's beliefs about child's ZPD formed from its knowledge about the amount of collaborative support used to date.	Record of help used to enable contingent calculation of next help level. Record of curriculum nodes visited maintained to permit suggestions.	Record of Curriculum nodes visited maintained to help child keep track.
Abstractness of Terminology selected by	system	child	child
Curriculum Node and phase of Ecolab complexity selected by	system	child - system makes suggestions	child
View selected by	mostly child	child	child

The *ability belief tag* values are percolated throughout the BBN whenever an activity is completed. This is in contrast to the *collaborative support tag* values which are only used to calculate the amount of collaborative support which will be needed for the next activity after that activity has been selected. In the current implementation of VIS all tag values start at zero and all children start at the first node which is about energy transfer. As soon as the child starts interacting at this rule node, records of help and differentiation level are recorded and these are used to update the *ability belief tags.*

When deciding which node to offer the child next there are various possibilities:

1. Stay at the same rule node at the same level of terminology abstraction - the same activity can be re-done or a different type of activity tackled.
2. Move to a new node employing any combination of less/more complex rule node with a less/more abstract level of terminology.

In the current implementation of VIS decisions are made on the following basis: upon completion of each activity the BBN is updated to take account of the collaborative support most recently provided. The amount of collaborative support a child actually used with a particular curriculum element (represented by a node in the learner model) is recorded. This may well be different to what the system predicted. This record is the *collaborative support tag* associated with that particular node in the learner model. Once an activity has been completed the amount of collaborative support that the system actually provided for that activity is used to assess the probability that this activity was within the child's independent ability. There are 18 possible combinations of help and activity differentiation (collaborative support). Each carries with it a certainty value which represents the extent to which a particular activity was within the child's independent ability when this amount of support was used. Each help level and each activity differentiation level can be associated with a value. The higher that value, the greater the system's belief that this activity is within the child's *independent* ability. In the model the probability values have been equally spaced across the range 0 - 1 and are an initial 'best guess' at appropriate values.

The *collaborative support tag* value is converted into the *ability belief tag* value for that node. The *ability belief tag* value represents the system's current belief that this element of the curriculum is now within the child's independent ability. An *ability belief tag* value of 1 associated with any of the nodes in the learner model indicates that the system believes that the learner needs no support to achieve success with this particular node in the curriculum. Such a node would not be a part of the learner's ZPD i.e. it's too easy. An *ability belief tag* value of less than 1 indicates that collaborative support will be required with this curriculum element. The pre-requisite relationships within the domain knowledge allow a partial ordering of the curriculum elements which in turn allows the use of conditional probabilities in a Bayesian Belief Network (BBN). If one node is linked to another node via a pre-requisite link it is part of an influential relationship, and the system's belief about this linked node will also be affected as updated beliefs are propagated throughout the network. Conditional probability values are associated with each pre-requisite link in the network. These values do not change over time and were initially given 'best guess' values. They are used to propagate the ability belief values between nodes.

Once the child has completed the introductory, exploration and rule-formation activities the *ability belief tag* value associated with a particular node in the learner model is compared to a threshold value (currently set at .3). If the *ability belief tag* value is equal to or greater than the threshold then a new node in the curriculum will be selected. The next node is selected as the node with an associated *ability belief tag* value which comes closest to, but below, the value associated with the just completed node, while respecting the pre-requisite structure of the network. This algorithm was selected in the current implementation in order to identify a node which is not too far from the learner's current capability. If the threshold value has not been reached then the child is offered another activity at the same node in the curriculum. Coherence of instruction is maintained through the pre-requisite links in the curriculum. The choice of a value of .3 for the threshold and the implementation of this decision algorithm are issues which were a 'best guess' on this first implementation; they are areas which require further attention.

Deciding how much collaborative support to provide

When the next node within the curriculum has been selected a decision must be made about how much collaborative support to provide. Calculations of future collaborative support rely upon a representation of the historical record of the amount of collaborative support the child has required previously and the *ability belief tag* value associated with the node which has been selected for the next activity.

Selecting the next Help Level

The level of help is the more flexible component of collaborative support. When an activity is completed the level of help actually used is compared to the level which was initially set. These can differ if, for example, the child found the activity harder than the system expected and used more help than was originally offered. An estimate is made of the level of help that should have been initially offered. By combining this with a weighted analysis (more recent activities weighted greater) of past help overall, an initial value of help for the next activity is arrived at.

This initial value is further adjusted according to the difficulty of traversing the pre-requisite link from the recently completed node to the next one. If it is a difficult step (as estimated a priori in the design of the knowledge representation), the value for the amount of help to be offered at the next node is increased.

Selecting the next Activity Differentiation Level

When deciding what level of Activity Differentiation to use next there are three possibilities: increase, decrease or stay the same. The aim is to ensure strenuous mental activity on the part of the child. This results in adherence to the motto "if possible reduce the amount of Differentiation used".

The following rules specify what should happen to the Activity Differentiation level:

If the level of Activity Differentiation in the just completed activity resulted in help of less than level 3 being used then reduce the level of the Differentiation unless it is already level 1.

If the level of Differentiation resulted in help of level 3 being used then stick to this level of Differentiation.

If the level of Differentiation resulted in help of more than level 3 being used then increase the level of the Differentiation, unless it is already level 3.

In other words, the next level of Differentiation to be used is modified by the amount of Differentiation just implemented and the help this required.

Level 3 help is considered significant in these rules, because at level 3 the nature of the help changes from general encouragement to specific identification of what needs to be done (see earlier section on Collaborative Support). At levels 4 and 5 the nature of the help is again slightly different. At these levels the specific actions necessary and the appropriate materials are identified for the child.

A more detailed description of the implications of a ZPD based approach and the way that these requirements have been implemented in the VIS variation of the software can be found in (Luckin, 1998).

Selecting the View

Whether the child sees the World view, Web view, Energy view or the other views is largely under her direct control. The main exception is when VIS draws the child's attention to Energy view during her activity at the Energy Transfer rule node of the curriculum.

LEARNING WITH THE 'ECOLAB'

Experimental Design

The design framework implemented within VIS, WIS and NIS was evaluated to explore the hypothesis that:

Interactions with the VIS variation of the Ecolab will prove most efficient at creating interactions consistent with the ZPD thesis: these interactions will target the collaborative resources of the system's ZAA to the ZPD of the individual learner. In other words, it will tune collaborative assistance more appropriately.

A group of 30 children, all aged between 10 and 11 years took part. To be an effective learning partner the system needs to be able to adjust to learners of differing abilities. The children's school assessments were therefore used to allocate each child to one of three ability groupings: High, Average and Low. The children were then divided into three groups matched for spread of ability, each of which used a different Ecolab system variation. Prior to using the software each child completed a written and a verbal pre-test, details of which can be found in Appendix 1. Each child used the Ecolab software as an individual for a total of 60 minutes over two sessions in their normal classroom environment. These interactions were logged. In addition, a 20 minute initial session with a smaller 'demo' version ensured that all children were comfortable with the mouse skills required and the interface. After the system intervention subjects were given a written and verbal post-test, identical to the pre-test. 26 children completed all parts of the evaluation procedure. The results of the pre and post-test were used to assess the efficacy of the three variations of the Ecolab software. The records of the interactions between each child and the system were examined to investigate what sorts of interactions had resulted in the greater learning gains. For more details of the experimental design and the subjects see Luckin (1998).

Results

The evaluation looked at whether the different variations of the Ecolab had been more or less effective in increasing the child's learning gain in terms of her understanding of the feeding relationships which exist in a food web. Improvement performance was investigated using an ANOVA [2 by 3 by 3, repeated measures] on the pre-test and post-test data. The design being 2 (T1:pre-test,T2:post-test) by 3 (VIS, WIS, NIS) by 3 (High Ability, Average Ability, Low Ability). The number of children in each condition is therefore small and the results discussed here can only be regarded as an interesting initial exploration. The overall effect of the interaction between Time and the System variation was significant ($F(2,17) = 3.79$ $p < .05$). This is illustrated in Figure 4 and indicates that the system variation which the child used was relevant to her subsequent learning gain. A post hoc analysis indicated that the significant difference ($p < .05$) was between VIS and both WIS and NIS. The interaction between Time, System variation and Ability group was also significant ($F(2,17) = 5.63$ $p < .01$). Table 4 summarises these results.

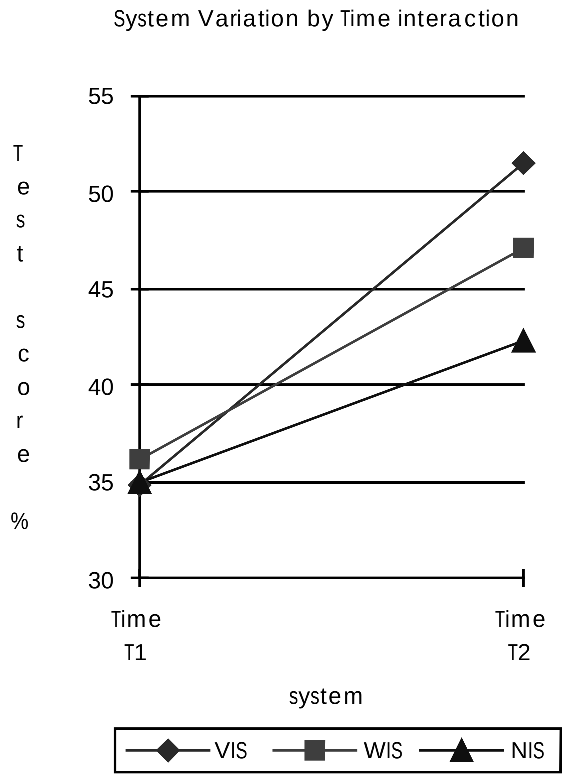

Figure 4. The Interaction between time and Ecolab system variation

Table 4. Summary of Mean Learning Gains

Mean improvement between pre & post-test. Score % (S.D.)	VIS	WIS	NIS	Total. post - pre = improvement
High Ability group	20 (6.38) n = 3	23.33 (6.00) n = 3	1.66 (2.35) n = 3	58.95 - 43.97 = 14.98
Average Ability group	13.88 (6.73) n = 4	3.75 (6.14) n = 4	5.42 (2.84) n = 3	40.53 - 32.65 = 7.88
Low Ability group	14.16 (8.24) n = 2	6.66 (0) n = 2	16.66 (2.35) n = 2	37.61 - 25.11 = 12.5
Total	51.48 - 34.81= 16.67 (6.72)	47.03 - 36.11= 10.92 (10.54)	42.29 - 35.00= 7.29 (6.42)	11.79 (8.79)

The significant interaction between the system variation used and the learning gains made by the children offers some support for the selection of constituents which make up the ZAA of VIS and for allocating control for the composition of the ZPA to the system. However, whilst VIS resulted in the most consistent learning gains across all abilities the significant three way interaction between system variation, ability and learning gain indicate that it was not the optimal system with children of all abilities. The mean improvement amongst WIS users who were in the high ability group was greater than those for VIS and NIS. Likewise the mean learning gains for low ability NIS users were higher than those for WIS and VIS. These differences have to be treated with caution because of the small number of children in each cell.

In order to examine VIS as an implementation of its ZPD inspired design framework, the available assistance and the children's use of it was evaluated. The range of assistance which can be made available to the child when using the Ecolab software was discussed earlier and has been referred to as the system's ZAA. It consists of the following basic elements of assistance:

- Extension
  Across to a more complex aspect of the food web curriculum
  Up to a more abstract level of description
- Collaborative Support under the control of VIS
  Activity differentiation
  Help of 5 different levels

Certain movements horizontally between rule nodes are sufficient to take the child from one phase to another and thus to produce a World Differentiation. These larger changes are recorded separately from extensions up and across which may leave the child in the same phase (or world). View changes were largely under the child's control even in VIS, and completely under her control in WIS and NIS. The degree to which children exploited this facility is also shown in Figure 5. The evaluation recorded each time a child used one of these forms of assistance. Figure 5 illustrates the percentage of children who used the various different types of assistance within the system's ZAA during their interactions with the Ecolab. It indicates that there were members of the WIS and VIS groups who made use of all the different types of assistance available. A greater percentage of VIS children used each of the different types of assistance than either WIS or NIS.

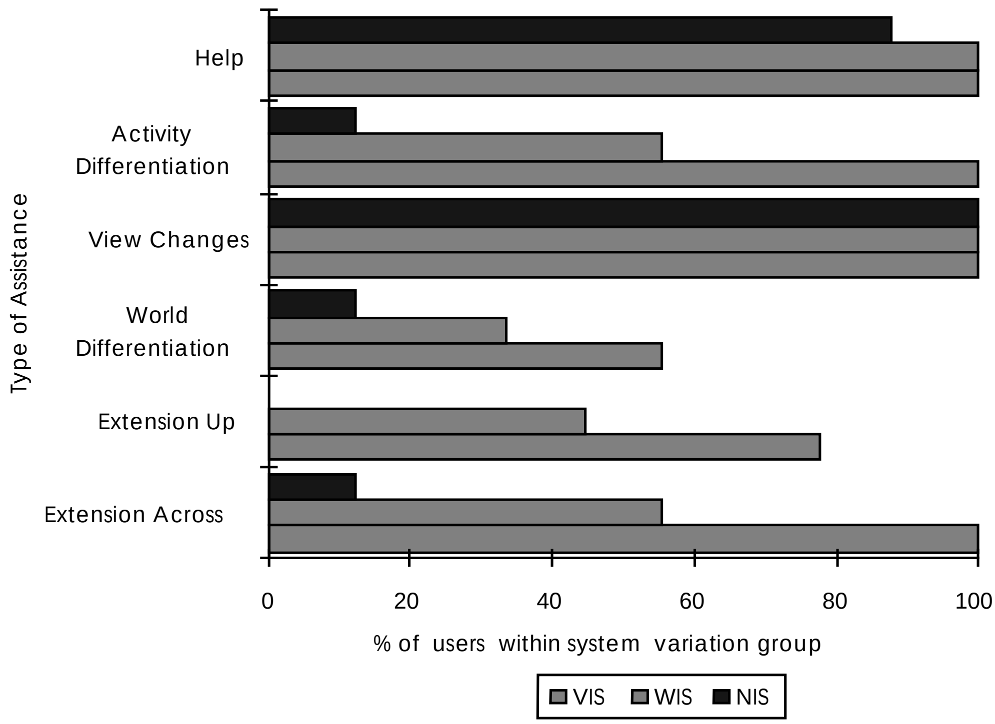

Figure 5. The percentage of children who used the various different types of assistance

A one way ANOVA examined the effects of system on the number of types of assistance used. This effect was significant ($F(2,25) = 16.38$, $p < .01$). A post hoc Bonferroni test indicated that the significant difference was between the number of assistance types used by NIS children and that used by the other two system variations groups: WIS and VIS ($p < .05$). The percentage of users from each of the system variations who used a particular number of different types of assistance indicates that VIS and WIS learners accessed a greater number of the different types of assistance than their NIS counterparts. All of the children using VIS and 79.2% of the children using WIS accessed 4 or more of the different types of assistance available. However, 87% of the NIS children tried less than 4 different types of assistance and none of this group tried more than 4.

DISCUSSION

VIS as an implementation of the ZPD

The analysis of the children's interactions makes it clear that VIS users took advantage of the greatest variety of available system assistance. Figure 5 illustrates the comparison between the three system variations. This shows that both WIS and VIS children used all the available types of adjustment, whilst NIS children did not. In addition, 88% of VIS children used 5 or 6 types of assistance as compared to 35% for WIS and 0% for NIS. These results support the suggestion that VIS users took the greatest advantage of the system's ZAA. However, for there to be more conclusive support for the hypothesis that VIS is the most effective at creating interactions consistent with the child's ZPD, this assistance needs to be shown to have been effective. The efficacy of VIS in terms of learning gains provides some support for the appropriateness of the system adjustments that VIS users experienced. There was a significant interaction between the system variation a child used and her post-test learning gain. VIS was the most consistent system across the ability groups, although it did not produce the highest learning gain in each of the categories.

The variations in learning gain in the different ability groups and in relation to the system variation used are interesting and somewhat counterintuitive. The most successful system with the low ability learners was NIS and yet it was the system which required the learner to take the most responsibility for selecting the activity, the differentiation level and for requesting help. One possible explanation could be that VIS tried to extend children too quickly, whereas NIS allowed them to spend as much time as they wanted with the simplest activities. Alterations to the threshold used in making decisions about which area of the curriculum to offer a learner next in future implementations of the Ecolab might enable this suggestion to be explored. There is certainly some supporting evidence within an analysis of the interactions each child had with the system (Luckin, 1998). Low ability children showed a tendency to tackle fewer activities and to persist with a particular activity once started. As regards low ability users and WIS, a possible explanation might be that the suggestions made by the system about what to do next and how much help to accept required too much processing and interrupted the learner from concentrating upon a particular activity. The fact that WIS was the most effective system with children in the high ability group may be due to the ability of these children to make decisions for themselves about how difficult an activity they should try and how much help they should adopt. Similarly the performance of WIS with the least able children may well indicate that the least able children were the least willing to accept the suggestions made by WIS about attempting activities which they felt were difficult, or accepting a particular level of differentiation and help. Deriving reliable data about aptitude treatment interactions is a difficult business (see e.g. Cronbach and Snow, 1977 for a review). In the current case the number of subjects in each cell is too small to draw firm conclusions about the apparent success of WIS with low ability subjects.

In many ways the VIS, WIS, NIS variation is exactly the kind of macroadaptive dimension described by Shute (1993, 1995), with the subject specific adaptivity of VIS and WIS corresponding to her notion of microadaptivity. Her own studies of aptitude treatment interactions have produced a not dissimilar result in terms of the successful exploitation of lower ability learners of a freer learning condition. For example, Shute and Gawlick-Grendell (1994) found that high ability subjects performed slightly better when using her Stat Lady system compared to a workbook. But she found that low ability subjects performed slightly better (but not significantly) using a workbook than the system. All of this is necessarily speculative, but interesting nevertheless.

The evidence discussed supports the suggestion that VIS did construct the ZPA it used with each child in a manner which proved beneficial to her interactions and subsequent learning gain, although there is some evidence which supports the view that the needs of the lower ability children need further attention. This may be due to limited exposure to the system or incorrect setting of probability values in the BBN. To this extent VIS has not met its design specification in terms of the operationalisation of a learner model which reflects the child's potential most effectively. There is therefore only partial support for the hypothesis. Certainly VIS adjusts to its users to a greater extent and some of its users learn significantly more than WIS and NIS users; however, these adjustments may or may not be the optimal for each child's ZPD.

The ZPD can be viewed as the crystallisation of the relationship between learning and development. Through its emphasis upon interaction the view that the teaching and learning processes must be considered together is promoted. The interpretation underlying the Ecolab highlights the centrality of the need for collaboration. This collaboration is between the less and the more able members of a learning relationship. The more able members take responsibility for extending and supporting the learner as she moves beyond the realms of her independent ability. The essential nature of the active participation of the more able and the less able is recognised.

The concepts of a Zone of Available Assistance (ZAA) and a Zone of Proximal Adjustment (ZPA) have been used to clarify the interpretation of the ZPD within the Ecolab. These two concepts explain the role of the more able learning partner, whether human or computer. They provide a useful means of specifying what assistance the system can provide for the learner. The use of these concepts emphasises the need for a quantification of the more able partner role prior to embarking upon the software design process. This emphasis upon the more able partner role is continued into the learner model maintained by VIS. This model is described as a representation of the system's beliefs about the learner's ZPD. These beliefs are however based upon the measurement of the collaborative support that a child has already used and which the system 'believes' she will need in the future.

The Design Framework

Each of the features in the design framework used in the implementation of VIS, WIS and NIS has played a part in the overall success of the Ecolab. The most salient features are:

- The method adopted for the representation of the system's knowledge about food webs which allowed the construction of a systematically organised fabric of scientific concepts. Within this fabric there are potential links to the concepts already experienced by the child. This structure recognises the differentiation between the scientific and everyday concepts emphasised by Vygotsky and the importance of the mediational role played by the concepts the child already understands (Vygotsky, 1986). This representation also allows the use of probabilities for the systematic introduction of these scientific concepts within the VIS variation.
- The allocation of values to each element of the collaborative support provided by help interventions and activity differentiation offers a method of quantifying this support, and as a consequence, of quantifying the user's capability.
- The learner model within VIS provides a means of recording a child's independent ability and collaborative capability. These records can then be used in the formation of the system's beliefs, allowing the maintenance of a dynamic, ZPD-inspired user model.
- The presence of the activity templates and their linkage to the rule nodes of the curriculum and to the action commands of the environment permits the construction of clearly defined goals towards which the child can direct her activity.
- The variety of organisms, commands and views promotes the user's creativity whilst allowing her to adhere to the requirements of the current activity goal.
- The direct manipulation interface allows the learner to interact with her environment and to direct activity towards her requirements. The consistency of this interface with those previously experienced by the children in the evaluation study promotes its accessibility.
- The availability of alterations to the abstractness of the terminology used to describe the objects of the Ecolab offers the user opportunities to decontextualise the objects mediating her experience of the curriculum.
- The accessibility of the interface, the possibility of extension and the availability of collaborative support encourages the child's engagement with the concepts of the curriculum as well as the features of the interface.
- The collaborative approaches of the three system variations provides different ways of encouraging the extension of the child beyond her independent ability. VIS makes an explicit attempt at extension through selection of the curriculum area for the child's activities.
- The provision of various types of assistance and a strategy for selecting the use of this assistance through the system's adjustment to the user provides flexible collaborative support for her activities.
- The integration of the computer based activities within the normal everyday activities of the classroom respects the culturally specific nature of this environment.

CONCLUSIONS

The Ecolab project has offered one way of using the ZPD as the basis for a software Design Framework which has been implemented and evaluated. This evaluation has demonstrated that the design framework is effective in assisting a single user to learn about the relationships which exist within food webs. It has illustrated that different styles of interaction and collaboration can be supported within an interactive learning environment. The Ecolab project has also offered a methodology for evaluating one approach to the use of Vygotsky's instructional theory in software design. The significant interaction between the system variation a child used and her post-test learning gain, plus the fact that VIS was the most consistent system across all the ability groups supports the approach adopted. The evaluation of the Ecolab also highlights the need for learners to be extended and illustrates that providing children with the means for extension through becoming involved in challenging activities is not enough to ensure that these challenging activities are undertaken. Learners need to be explicitly directed towards activities which are beyond their ability. The ILE needs to have the capability to take control for the allocation of subject area and assistance. However, the success of the WIS system variation indicates that a suggestion about what and how to proceed is often sufficient. This highlights the need for balance between system direction and user creativity and offers a focus for future research. A system which can assist a learner to take more control for her own extension, which models a learner's developing collaborative skills as well as her developing understanding of the curriculum is the logical extension to the Ecolab system.

Much work remains to be undertaken. A larger evaluation is needed. The small number of subjects in the evaluation means that the results remain tentative, especially those relating to ability treatment interactions where the numbers in each cell were very small. The probability values attached to the prerequisite links, the allocation of certainty values to the different combinations of help level and activity differentiation, and other 'best guess' decisions need putting on a firmer foundation. The methodology applied by Shute (1995) will be of value here.

Acknowledgements

This research was sponsored by the Economic and Social Research Council. We would also like to thank David Wood and Yvonne Rogers, Mike Scaife and Mike Sharples for useful discussion and insightful comment upon this work, and the children and teachers of Blacklands School, Hastings.

References

Adey, P. (1996). *Cognitive acceleration and the zone of proximal development. (conference presentation).* Paper presented at the abstracts of the IInd Conference for socio-cultural research, Geneva, September, 1996.

Alexander, S. K. (1982). Food web analysis: An ecosystem approach. *The American Biology Teacher, 44*(3), 189-190.

Anderson, J. R. (1976). *Language, memory and thought*. Hillsdale: Erlbaum.

Anderson, J. R. (1984). On the merits of ACT and information-processing: A response to Wexler's review. *Cognition, 8*, 73-88.

Anderson, J. R., Corbett, A. T., Koedinger, K. R., & Pelletier, R. (1995). Cognitive tutors: lessons learned. *The Journal of the Learning Sciences, 4*(2), 167-207.

Becker, J., & Varelas, M. (1995). Assisting construction: The role of the teacher in assisting the learner's construction of pre-existing cultural knowledge. In L. P. & Steffe J. Gale. (Ed.), *Constructivism in Education* (pp. 433-446). Hillsdale. NJ: Lawrence Erlbaum Associates.

Chan, T. W., Lin, C. C., Lin, S. J., & Koo, H. C. (1993,). *OCTR: A model of learning strategies*. In Brna, P. Ohlsson, S. and Pain, H. (Eds.), *Artificial Intelligence in Education* (pp. 257-264). Charlottesville: AACE.

Cronbach, L.J. and Snow, R.E. (1977). Aptitudes and Instructional Methods: A Handbook for Research on Interactions. New York: Irvington.
Evans, P. (1993). Some implications of work for special education. In H. Daniels (Ed.), *Chartering the Agenda: Educational activity after Vygotsky* (pp. 30-45). London: Routledge.
Goldstein, P. (1982). The genetic graph: a representation for the evolution of procedural knowledge. In D. Sleeman. and J. S. Brown. (Ed.), *Intelligent Tutoring Systems*. New York: Academic Press.
Griffiths, A. K. Grant, A.C. (1985). High school students' understanding of food webs. *Journal of Research in Science Teaching, 22*(5), 421-436.
Guzdial, M., Kolodner, J., Hmelo, C., Narayanan, H., Carlson, D., Rappin, N., Hubscher, R., Turns, J., & Newstetter, W. (1996). Computer support for learning through complex problem solving. *Communications of the ACM, 39*(4), 43-45.
Hativa, N. & Lesgold, A. (1991). The computer as a tutor - can it adapt to the individual learner? *Instructional Science, 20*, 49-78.
Howard, R. W. (1987). *Concepts and schemata : an introduction*. London: Cassell.
Koedinger, K. R., Anderson, J. R., Hadley, W. H., & Mark, M. A. (1997). Intelligent tutoring goes to school in the big city. *International Journal of Artificial Intelligence in Education, 8*, 30-33.
Luckin, R. (1998). *'ECOLAB': Explorations in the Zone of Proximal Development* (CSRP Technical Report 486): School of Cognitive and Computing Sciences, University of Sussex.
Lumpe, A. T. Staver, J. R. (1995). Peer collaboration and concept development: learning about photosynthesis. *Journal of Research in Science Teaching, 32*(1), 71-98.
Merrill, M.D. Tennyson, R. & Posey, L.O. (1992). *Teaching Concepts*. Englewood Cliffs: Educational Technology Publications.
Murphey, T. (1996). *Proactive adjustment to the zone of proximal development.* Paper presented at the abstracts of the IInd Conference for socio-cultural research. September 1996, University of Geneva.
Pedersen, S. & Hallden, O. (1994). Intuitive ideas and scientific explanations as parts of students' developing understanding of biology: The case of evolution. *European Journal of Psychology of Education, 9*(2), 127-137.
Rosch, E. (1988). Principles of categorization. In A. Collins. & E. A. Smith (Ed.), *Readings in Cognitive Science*. San Mateo: Morgan Kaufmann.
Shute V. J. (1993). A Comparison of Learning Environments: All that Glitters. *Computers as Cognitive Tools.* S. P. Lajoie & S. J. Derry (Eds). Lawrence Erlbaum Associates}, Hillsdale, New Jersey},
Shute, V., J. (1995). {SMART}: Student Modelling Approach for Responsive Tutoring. *User Modelling and User-Adapted Interaction, 5*(1), 1-44.
Shute, V., J. , & Gawlick-Grendell, L., A. (1994). What Does the Computer Contribute to Learning? *Computers and Education, 23*(3), 177 -186.
Shute, V. J. (1993). A Comparison of Learning Environments: All that Glitters. In S. P. Lajoie & S. J. Derry (Eds.), *Computers as Cognitive Tools* (pp. 47 -73). Hillsdale, New Jersey: Lawrence Erlbaum Associates.
Soloway, E., Jackson, S., Klein, J., Quintana, C., Reed, J., Spitulnik, J., Stratford, S. J., Studer, S., Eng, J., & Scala, N. (1996). *Learning theory in practice: Case studies of learner-centred design.* Paper presented at the CHI 96 Human Factors in Computing Systems: Common Ground, Vancouver. pp 189-196
Tennyson, R. D., Christensen, D. L. and Park, S. I. (1984). The Minnesota adaptive instructional system: an intelligent CBI system. *Journal of Computer Based Instruction, 11*(1), 2-13.
Vygotsky, L. S. (1978). *Mind in society: the development of higher psychological processes* (M. Cole, V. John-Steiner, S. Scribner, E. Souberman, Trans.). Cambridge, MA: Harvard University press.
Vygotsky, L. S. (1986). *Thought and language*. Cambridge, Mass: The MIT Press

Vygotsky, L. S. (1987). *Problems of general psychology*. (Vol. 1). New York: Plenum Press.

Wood, D., Shadbolt, N., Reichgelt, H., Wood, H., & Paskiewitz, T. (1992). EXPLAIN: Experiments in planning and instruction. *Society for the Study of Artificial Intelligence and Simulation of Behaviour Quarterly Newsletter*, *81*, 13-16.

Wood, D. J., Wood, H. A. & Middleton, D. J. (1978). An experimental evaluation of four face-to-face teaching strategies. *International Journal of Behavioural Development, 1*, 131-147.

Wood, D. J., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. *Journal of Child Psychology and Psychiatry*, *17*(2), 89-100.

APPENDIX 1

Children were evaluated via pre and post written tests and via pre and post structured interviews. The interviews were conducted by an accomplice who did not know which group the children were in. Scoring of the written tests and of the interview transcripts were checked by the accomplice.

The overall evaluation scheme was designed to assess the evidence that the child understood the following 17 issues:

Evaluation scheme for written and verbal tests

Aim: to find evidence that the child understands that:

Feeding relationship between 2 organisms

1. That when one organism eats another energy is passed from the organism that is eaten to the organism that eats it - that the arrow in the food web depicts the 'eaten by' relationship between 2 organisms.
2. That in a simple feeding relationship between 2 organisms the feeding organism will be affected by what it eats - in particular, changes in the existence of the organism that **it eats**
3. That in a simple feeding relationship between 2 organisms the food organism will be affected by the organism that eats it - in particular, changes in the existence of the organism that **eats it**
4. That some organisms are predators and that some organisms are prey

Food Chains

5. That in a food chain the feeding organism at the top will be affected by an organism lower down the chain - in particular, changes in the existence of the organism that is the food of the organism that it eats i.e. the organism at the bottom
6. That in a food chain the food organism at the bottom will be affected by an organism higher up the chain - in particular, changes in the existence of the organism that is the feeder of the organism that eats it i.e. the organism at the top

Food Webs

7. That food webs connect different organisms so that changes in the existence of an organism can affect other organisms in the web which are part of a different food chain

8. That in a food web a feeding organism near the top will be affected by an organism lower down the web - in particular, changes in the existence of an organism that is lower down the food web through more than 1 food chain route
9. That in a food web a food organism near the bottom will be affected by changes in an organism higher up the chain - in particular, the existence of an organism that is higher up the food web through more than 1 food chain route
10. That the effects of changes in the existence of organisms anywhere in the food web are passed to other organisms via many different food chain routes
11. That (leading on from point 10 above) the organisms in different food chains within the food web can be affected by changes in the existence of other organisms via many food chain routes
12. That plants are the key member of any food web or ecosystem and that they are the only organisms that can produce food.
13. (extending to point 12 above) That sunlight is essential for the production of food and that this means that it is essential for all organisms

Ability to abstract away from specific examples

14. That the child has moved beyond the point of considering individual organisms or groups of organisms of a particular species and can consider them as instances of a type e.g. a herbivore, consumer, producer
15. (extending point 13 above) That the child can consider the food web as a provider of information about the nature of the organisms even if there is no information about the actual identity of a particular organism

Awareness of what he or she has learnt

16. That the child is aware of what they have learnt and is able to explain it at a particular level of abstraction and complexity

Transfer of knowledge to different situation

17. That the child can use her knowledge when considering novel situations - i.e. different to that portrayed in the specific examples of the system or the rest of the test. (The examples in the test do already require application to a slightly different scenario to that in the system)