Capability, Potential and Collaborative Assistance

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Abstract. This paper is concerned with the issue of adjusting the complexity, content and assistance in interactive learning environments (ILEs). In particular, it describes the structure and evaluation of the learner model implemented within VIS (the Vygotskian Instructional System). This software explores the way that Vygotsky's Zone of Proximal Development can be used in the design of learner models. This theoretical foundation requires the system to adopt the role of a more able assistant for a learner. It must provide appropriately challenging activities and the right quantity and quality of assistance. The learner model must track both the learner's capability and her potential in order to maintain the appropriate degree of collaborative assistance. Within VIS the learner model is a Bayesian Belief Model overlay of the domain knowledge structure. An evaluation of the system illustrates that the approach adopted by VIS promotes the construction of productive interactions with the majority of learners, across a range of abilities. The learner model within VIS is in effect an operational definition of the ZPD of each learner who interacts with the system

1 Introduction and outline of what is to come

The Zone of Proximal Development (ZPD) (Vygotsky, 1978) is created when two or more people form a collaborative learning partnership in which the more able members enable the less able members to achieve their goal. In order for a collaborator to be successful in the role of a more able learning partner she must construct a shared situation definition (Wertsch, 1984) where all members have some common knowledge about the current problem. This intersubjectivity can only be achieved if the teacher/collaborator has a dynamic representation of the learner's current knowledge and understanding. The ZPD also has a spatial analogy which quantifies a learner's potential (Vygotsky, 1986). It is the fertile area between what she can achieve independently and what she can achieve with assistance from another. In essence the ZPD requires collaboration or assistance for a leamer from another more able partner. The activities which form a part of the child's effective education must be (just) beyond the range of her independent ability. The learning partner must provide appropriately challenging activities and the right quantity and quality of assistance. In VIS the learning partner role is adopted by the system, and so the learner model must track both the learner's capability and her potential in order to maintain the appropriate degree of collaborative assistance. This paper discusses the design of the learner model implemented in VIS. An evaluation of VIS enabled us to explore the types of computer experiences which appeared to lead to productive interactivity for children learning about food web concepts. Through examination of the way that the learner model in VIS helped to ensure this type of productive interactivity for each child, the following question could be addressed: What instructional leverage is gained through using the ZPD in the design framework?

The strong focus on adapting to the user by adjusting the amount of help that is initially offered is similar to the adaptive mechanisms in the SHERLOCK tutors (see e.g., Katz, Lesgold, Eggan, & Gordin, 1993; Lesgold, Lajoie, Bunzo, & Eggan, 1992). A difference is that there is also adjustment both to the nature of the activities undertaken by users and to the language in which these activities are expressed. The emphasis which VIS places upon extending the learner beyond what she can achieve alone and then providing sufficient assistance to ensure that she does not fail also sets it apart from other system's such as that of Beck, Stern and Woolf (1997), which generate problems of controlled difficulty and aim to tailor the hints and help the system offers to the individual's particular needs. VIS extends the work done with other systems which have used the ZPD concept in the learner modelling (e.g. Gegg-Harrison, 1992).

2 VIS and the Ecolab

The Vygotskian Instructional System (VIS) is part of the Ecolab Interactive Learning Environment (ILE) which aims to help children aged 10 -11 years learn about food chains and webs. The Ecolab provides a flexible environment which can be viewed from different perspectives and run in different modes and in increasingly complex phases. 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. The Ecolab can assist the child in several ways. First, it can offer 5 levels of graded help specific to the particular situation; second, the difficulty level of the activity itself can also be adjusted (activity differentiation). Finally, the definition of the domain itself allows topics to be addressed by the learner at varying levels of generality.

3 The learner model in VIS

In order to provide the collaborative support just described the learner model in VIS is based upon a set of beliefs about the child's ZPD. It is an overlay of the curriculum knowledge representation and consists of two hierarchies of linked nodes. One defines the phases of environment complexity and the other defines the levels of terminology abstractness. This structure is based upon an adaptation of Goldstein's Genetic Graph (Goldstein, 1982). The resultant links between the different organisms can be divided into two main categories:

Vertical dimension links: These connect concepts within the taxonomy 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 *primary consumer*. Although this taxonomy may not be entirely based upon the abstraction relationship, as the level increases the concepts are those which are less familiar to the child and more inclusive of the subordinate concepts. This dimension is represented in the Ecolab by the different levels of abstraction applied to the language used to describe the organisms in the simulated community.

Horizontal dimension links: These links define the concepts' degree of complexity within the world and the relationship which each concept bears to another (see Figure 1).

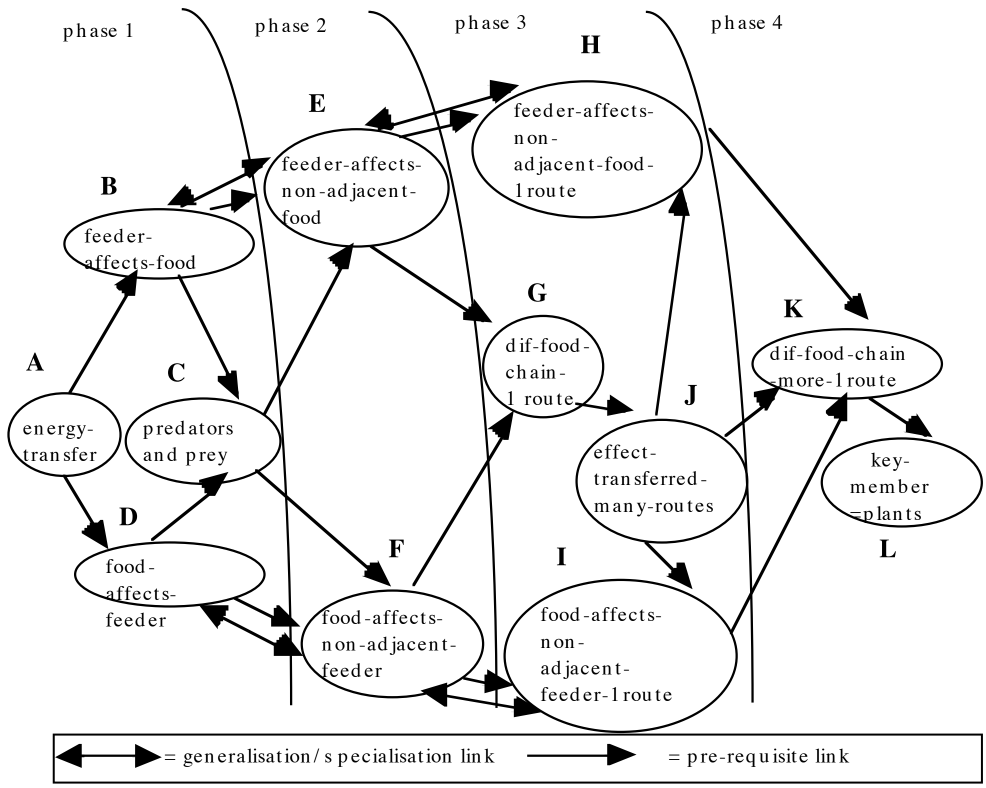

Figure 1 Network of food-web rules representing the horizontal dimension of the domain knowledge

These relationships themselves form a hierarchical structure put together in terms of the complexity of the particular relationship. For example, the *eat* relationship existing 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. Each relationship which is possible between organisms in the Ecolab is defined by a rule represented by a node in Figure 1. Each of these rules is associated with one of the commands the child uses to activate organisms in her environment. 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. A set of activity templates is associated with each rule node, these present her with activities which focus on the associated rule. The complexity of the relationship described by the rule 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.

In the domain knowledge representation each node represents an element of the curriculum, something which the child needs to understand: a relationship or a level of terminology abstraction. In the overlay learner model there are 2 values, or *tags*, associated with each node. The first value: the *ability belief* tag is the system's 'belief' about the child's independent ability.

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 at that node. 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.

3.1 Forming Beliefs about the learner's capability

The learner model must enable VIS to quantify which areas of the curriculum are beyond what the learner can use on her own, but within the bounds of what she can use 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 and therefore have a high *ability tag value* close to 1; which nodes are outside her independent ability and have a lower *ability tag value*; how much support needs to be provided in order to ensure that the learner is successful when interacting at a node with an *ability tag value* lower than 1. The overall instructional strategy is to aim for success at each node, rather than failure followed by remediation.

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 node's *collaborative support tag*. 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 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. The higher the value, the greater the system's belief that this activity is within the child's <u>independent</u> ability. In VIS the probability values have been equally spaced across the range 0 - 1 and are an initial 'best guess' at appropriate values (see Table 1).

Help Level Differentiation	0 0	0 1	0 2	1 0	1 1	1 2	2 0	2 1	2 2	3 0	3 1	3 2	4 0	4 1	4 2	5 0	5 1	5 2
Certainty	1	.83	.67	90	.73	56	.80	.63	.46	.70	53	36	.60	.43	.26	50	33	.16

Table 1: certainty values attributable to the possible combinations of help and differentiation

3.2 Drawing inferences about a learner's potential.

The pre-requisite relationships within the domain knowledge allow a partial ordering of the curriculum elements. In the horizontal (complexity) dimension node *n* needs to be tackled before node *n+1* where *n* is connected to *n+1* by a pre-requisite link. In the vertical (terminology abstractness) dimension the hierarchy is quite specific, level 1 first then 2 and so on. This partial ordering allows the use of conditional probabilities in a Bayesian Belief Network (BBN). Each *ability belief tag* in the learner model is a representation of the system's belief about the extent to which that element of the curriculum is within her independent ability. This information is used to quantify the child's ZPD. Evidence from interactions at a particular rule node will alter the system's belief about that node and its membership to the set of nodes which constitute the child's independent ability. In addition, if the node in question 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 (Reye, 1995). The learner model must be constantly updated to take into account the changing situation as the child continues to interact with the system. The conditional probability element within VIS allows the maintenance of this dynamic representation of the extent of the child's ability. Once an *ability belief tag* value has been calculated, Bayes Theorem is used as the basis for propagating a new value for each of the other *ability belief tags* in the learner model (Jensen, 1996).

In addition to the existence of influential relationships within both the horizontal and vertical dimensions, and the potential for inference passing that these relationships afford, there is also the possibility of being able to pass inferences in both directions of the network. This possibility requires that there is a specification of the reverse relationships which exist between nodes. An allowance for the possibility of forgetting as well as acknowledgement of the value assigned to the forward transition counterpart is included in these reverse relationships.

4 Using the ZPD learner model to individualise instruction

Before the child starts an activity the system will have allocated a value to the *ability belief tag* for the current rule node in the learner model. This value represents the system's belief about the extent to which this rule is within the child's ability. As the child interacts with the system and completes the activities based around this rule, the belief held by the system will vary in accordance with the amount of collaborative support the child actually uses (see Table 1). In the current implementation of VIS a very conservative view of prior knowledge is taken and so all values start at zero. All children start at the first node *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 tag* from zero.

4.1 Deciding what activity to offer next

When deciding which node to offer the child next there are various possibilities: 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 on the same topic is tackled), or move to a new node. The new node may be a more or less complex rule node (a move forward, to the right in Figure 1, across the horizontal dimension OR backward across the horizontal dimension) and/or a rule node using a different level of terminology abstraction (a move up or down the vertical dimension)

In the current implementation of VIS decisions are made on the following basis: upon completion of each activity the *ability belief tag* values in the BBN are updated to take account of the collaborative support most recently provided (see Table 1). If the activity is other than the introductory activity 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. This algorithm was selected in the current implementation in order to select 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. Once all activities at a node have been completed, the network is updated and searched for a node with an *ability belief tag* value which is closest to, but higher than the current node. The choice of a value of .3 for the threshold was motivated by the desire to set a value which reflected that the system is aiming to extend the child onto activities which are outside her independent ability whilst at the same time avoiding over-extension beyond what she can achieve even with support. The choice of this threshold and the implementation of this decision algorithm are issues which are on this first implementation a 'best guess'. They are areas which require further attention.

4.2 Using the model to decide how much collaborative support to offer

Recall that the educational strategy is that the learner should successfully complete any node tackled if at all possible even if that means that the system, as the more able partner, provides a huge amount of assistance. When the next node within the curriculum has been selected a decision about how much collaborative support to provide is made using the *ability belief tag* value associated with the newly selected node and the *collaborative support tag* values which contain information about how much support the child has used previously.

The level of help is the more flexible component of collaborative support. The historical record of past help given to a learner is used to calculate the amount of help considered most appropriate for a particular learner: that learner's preferred help level (pfH). The help value for each previously visited node is weighted so that the most recently tackled activities contribute most to future decisions. The value of the next level of help to be offered to the child is set at the level of pfH (preferred help level), modified by the *ability belief tag* value associated with the next node and the difficulty of the transition from current to next node. The difficulty of the transition p(n+1|n) to the next node (n+1) is specified in the probability table reflecting the relationship between it and the just completed node n. The lower the value assigned to the relationship, the harder the transition from n to n+1 is perceived to be. A fragment of this table for movement across the horizontal dimension of Figure 1 is shown in Table 2.

Relationship	p(A)	p(B|A)	p(D|A)	P(C|B,D)	p(E|B,C)	p(F|C,D)
Associated Value	.8	.6	.8	.5	.5	.6
Relationship	p(G|E,F)	p(H|E,J)	p(I|J,F)	p(J|G)	p(K|H,I,J)	P(L|K)
Associated Value	.8	.5	.8	.5	.7	.6

Table 2 : Conditional probabilities in the horizontal dimension

Differentiation is measured in terms of the level of differentiation employed at the start of a particular activity. When deciding which of the three levels of 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". 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.

5 Evaluation

In addition to VIS there are two other system variations in the Ecolab: WIS and NIS. WIS is a system inspired by the contingent instructional approach (Wood & Middleton, 1975) and NIS is a system which allows the user a greater amount of autonomy in her selection of the collaborative support which the system will provide. The contingent teaching strategy requires a more able partner to take more control when the learner makes an error and then relinquish some of that control if the child is subsequently successful. 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. The learner model in WIS is simply a record of which activities have been completed, the identity of the most recent level of help used and whether or not this help lead the child towards success. By contrast, NIS maintains no learner model and allows the child herself to select the complexity and nature of the task, and the level of system support. With the exception of the quality and quantity of collaborative support given by the system and the implications this has for the interface, all three variations, VIS, WIS and NIS are identical.

The purpose of WIS and NIS is to allow a comparative evaluation of VIS. Observations of the way that learners interacted with the three systems were made as well as pre-post comparisons. This allowed an analysis of how the learner modelling in VIS affected learners of differing ability, and it also allowed a comparative analysis of the effects of switching out some (WIS) or all (NIS) of the adaptivity derived from detailed modelling. For full details of this evaluation see Luckin (1998) and Luckin and du Boulay (forthcoming). The children were all aged between 10 and 11 years of age. For the learner model within a system to claim efficacy it must be able to assist children of varying abilities. Prior to conducting this study the children had completed practice National and cognitive ability tests as part of the school's routine assessment procedure. These scores were used as the basis for allocating each child to one of three ability ranges: high, average and low.

There was a significant interaction ($F(2,17) = 3.79$ $p < .05$) between learning gain and system variation. Overall the mean learning gain amongst VIS users was greatest at 16.67% as opposed to 10.92% for WIS and 7.29% for NIS. A post hoc analysis indicated that the significant difference ($p < .05$) was between VIS and both WIS and NIS. There was a significant interaction ($F(2,17) = 5.63$ $p < .01$) between learning gain, system variation and ability. This evidence highlights the impact upon of the child's ability at the outset. A good learner model needs to be able to adjust to all abilities and offer appropriate support.

6 So Why was VIS more effective?

In order to examine the learner modelling in VIS as an implementation of its ZPD inspired design framework and to evaluate how well it adapted the system's collaborative assistance to children of differing abilities, the available assistance and the children's use of it was analysed.

The range of assistance which can be made available to the child when using the Ecolab software consists of the following basic elements of assistance:

1. Extension: **Across** to a more complex node OR **Up** to a more abstract level of description in the food web curriculum
2. Collaborative Support: Alterations to the complexity of the Ecolab environment: World differentiation i.e. moving between phases OR Alterations to the difficulty of the activities: activity differentiation OR Help of 5 different levels

During the evaluation each time a child used one of these forms of assistance it was recorded. 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. 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. A one way ANOVA examined the effects of system variation 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 WIS and VIS children ($p < .05$).

These results support the suggestion that VIS users took the greatest advantage of the system's collaborative support. The overall efficacy of VIS in terms of learning gains provides some support for the appropriateness of the system adjustments that VIS users experienced. However, for there to be more conclusive support for the hypothesis that VIS gains extra instructional leverage through operationally defining a child's ZPD, this assistance needs to be shown to have been effective in terms of learning gain. Figure 2 (left) differentiates the types of assistance used by learners who made an above average learning gain from the assistance used by learners making a below average learning gain. Figure 2 (right) differentiates the types of assistance used by learners according to system variation. These charts suggest that learners benefited from being challenged and extended *provided that* the activities were both differentiated appropriately and sufficient help was provided. VIS clearly extends all learners, indeed it is the only system variation to explicitly challenge learners in this way.

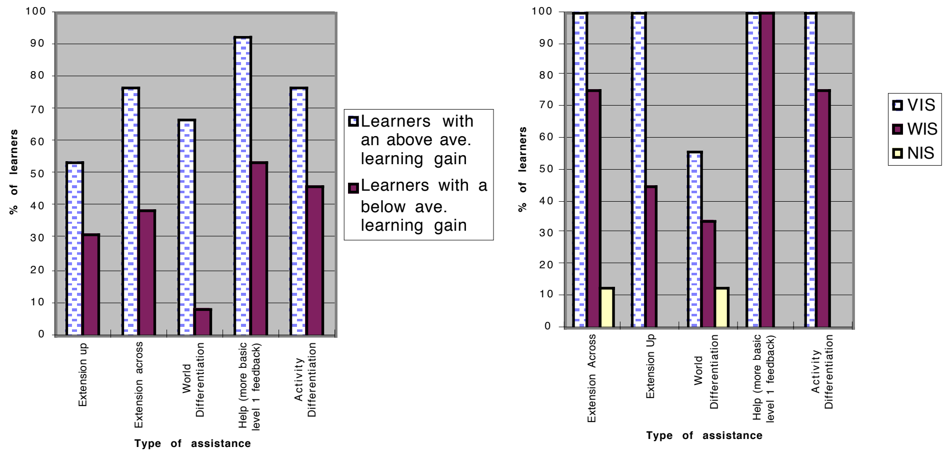

Figure 2: Assistance used by learning (left) and by system variation (right).

As has already been indicated, there was a significant interaction between the system variation a child used and her post-test learning gain. VIS was the most consistent variation across the ability groups. There is, however, some evidence that the needs of the lower ability children require further attention. Perhaps VIS extended the lower ability children too much, due perhaps to incorrect setting of probability values in the BBN. To this extent VIS has not completely met its design specification in terms of the operationalisation of a learner model that reflects the child's potential effectively. 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 optimal for each child's ZPD. The conditional probabilities used in the BBN were based upon information about which areas of the curriculum were known to cause children problems. These values could now be refined using the information about children's actual performance at the different nodes to inform this adjustment.

7 Conclusion

This paper has described a BBN-based learner model that operationalises Vygotsky's Zone of Proximal Development. This model has been implemented and evaluated both across a range abilities as well as against systems that switch out part of its functionality in an experiment similar to that carried out by Mark and Greer (1995). This has shown that the extra adaptivity enabled by the detailed model does lead to changes in learner behaviour and to learning gains.

Future work will involve refinement of the current model to take account of the inadequacies of its mechanisms and will increase its knowledge about how children learn about food webs. With regard to this latter point, and in accordance with the discussion of a dynamic ZPD above, the ability to alter the probability values attributed to each link in the learner model in the light of information gained as more children use the system will need consideration. Refinement of the learner model must also include attention to two particular aspects of the *individual differences* which were of particular note in the current evaluation: ability and learning style.

8 References

Beck, J., Stern, M., & Woolf, B. P. (1997). Using the student model to control problem difficulty. In A. Jameson, C. Paris, & C. Tasso (Eds.), User Modeling: Proceedings of *Sixth International Conferenceon User Modeling,* UM97. New York: Springer Wien. 278-288.

Goldstein, P. (1982). The genetic graph: a representation for the evolution of procedural knowledge. In D. Sleeman & J. S. Brown. (Eds.), *Intelligent Tutoring Systems*. New York: Academic Press.

Gegg-Harrison, T. S. (1992). Adapting instruction to the students capabilities. *Journal of Artificial Intelligence in Education*, 3(2), 169-181.

Katz, S., Lesgold, A., Eggan, G., & Gordin, M. (1993). Modelling the student in SHERLOCK II. *Journal of Artificial Intelligence in Education*, 3(4), 495-418.

Lesgold, A., Lajoie, S., Bunzo, M., & Eggan, G. (1992). SHERLOCK: A coached practice environment for an electronics troublshooting job. In J.H. Larkin & W. Chabay (Ed.*), Computer-Assisted Instructions and Intelligent Tutoring Systems*, pp 289-317 Hillsdale, NJ: Lawrence Erlbaum Associates.

Luckin, R. (1998). '*ECOLAB*'*: Explorations in the Zone of Proximal Development* (CSRP Technical Report 386): School of Cognitive and Computing Sciences, University of Sussex.

Luckin, R. & du Boulay, J.B.H. (forthcoming). Designing a Zone of Proximal Adjustment.to appear in *International Journal of Artificial Intelligence and Education*. Volume 10, 1999

Mark, M. A., & Greer, J. E. (1995). The VCR tutor: effective instructions for device operation. *Journal of the Learning Sciences*, 4(2), 209-246.

Jensen, F. V. (1996). Bayesian networks basics. *Society for the Study of Artificial Intelligence and Simulation of Behaviour Quarterly Newsletter*, 94, 9-23.

Reye, J. (1995). A belief net backbone for student modelling. In Frasson, C.; Gauthier, G & Lesgold, A. (Eds.), *3rd International Conference on Intelligent Tutoring Systems.* Lecture notes in Computer Science 1086 Berlin: Springer. 596-604.

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, MA: M.I.T. Press

Wertsch, J. V. (1984). The zone of proximal development: Some conceptual issues. In B. Rogoff & J. V. Wertsch (Ed.), *Children's Learning in the "Zone of Proximal Development"* (Vol. 23, pp. 7-18). San Francisco: Jossey-Bass.

Wood, D. J., & Middleton, D. (1975). A study of assisted problem solving. *British Journal of Psychology,* 66, 181-191.