A METACOGNITIVE APPROACH TO TEACHING MATHEMATICS THROUGH COMPUTER SUPPORTED ENVIRONMENTS

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The research reported here focussed on the mathematical learning of "at risk" preschoolers in computer-supported interactive environments. Specifically, our investigations have explored the effectiveness of metacognitively-rich computer-supported contexts on early mathematical learning. Results indicated that children who participated in mathematical learning activities within these contexts performed significantly better in tests of mathematics competence than did children engaged in more regular instructional approaches, including those situated within computer-based settings.

This paper presents some of the theoretical background to our research, some findings, and considers a range of implications for teaching mathematics in early childhood contexts.

In the research outlined in this paper we investigated the mathematical learning of "at risk" preschoolers in computer-supported interactive environments. Specifically, there are three theoretical perspectives that inform the research. The first is concerned with Vygotskian notions of the role of social mediation in scaffolding cognitive activity and the importance of self-regulatory strategies in internalising thinking. Secondly, we are concerned with aspects of cognitive science, in particular the processing of information, for example cognitive structure and how metacognitive activity improves storage and retrieval of data. Finally, there is a mathematics education perspective in which we consider optimal instructional approaches for early mathematical learning.

According to Vygotskian perspectives on cognitive development the interpersonal nature of cognitive activity is critical to learning. In this sense children's interactions with competent others serve to mediate thinking and problem-solving in the cognitive space between what can be accomplished alone and in collaboration with more capable others, that is, in the zone of proximal development. It is suggested that this "scaffolding" may provide ongoing stimulation and motivation for learning, as well as support of a more metacognitive, and particularly, self-regulatory nature. Subsequently, the self-regulatory strategies are internalised to become part of the learner's independent repertoire of competencies for application in similar and novel contexts (Rogoff, 1990; Vygotsky, 1978).

The role of the teacher in this scaffolding process is to promote an awareness of the cognitive demands of the task and to guide activity within a purposeful and goal directed framework focussing on, for example, overall task orientation, and planning, monitoring and evaluating cognitive activity, rather than on the management and organisation of the learning experience itself. Complementary peer interaction, as well as the individual's own structuring of the activity, generate the cognitive and metacognitive dialogues that serve to support and mirror knowledge and thinking. In this sense the interrelatedness of the contextual supports lend themselves to framing aspects of self-regulated learning.

While this interactivity is usually envisaged as mediated by adults and/or peers, computer environments may afford additional and complementary scaffolds through provision of prestructured content and in-built cognitive supports, for example, feedback, sequencing, and the predictable flow of a the activity. It is contended that intertwining these cognitive supports with those afforded by co-participants (teachers and peers), as well as the individual's own structuring of activity, serves to foster thinking and problem-solving (Salomon, 1990).

A key function of self-regulatory behaviour is its role in helping children increase their control over learning and problem-solving activity and the application of knowledge about cognitive states and processes to the learning process (Wellman, 1985; Zimmerman, 1990). For preschoolers, this cognitive activity, generally manifested at an external level and evidenced largely through language, results in the gradual internalisation of thinking skills (Vygotsky, 1978).

Our research is concerned also with how data are processed in the brain. In particular, we are interested in declarative and procedural knowledge and the roles of representations and analogies in assisting the movement from declarative to procedural knowledge. Specifically, we are concerned with ways in which learners can be encouraged to develop a richly connected cognitive network of skills and understandings. For example, teacher generated questioning designed to extend new learning and link it with present knowledge facilitates proceduralisation of the declarative knowledge initiated by the computer. Subsequent practice makes a learner's response time quicker, and the metacognitive scaffolds encourage chunking of related concepts or procedures. Through this process recall becomes faster and the efficiency of short term memory processing is increased. Central to this information processing are the self-regulatory strategies that enable learners to consciously control the processing of data in short term memory, and its flow in and out of long term memory. An individual's awareness and use of metacognitive strategies is increasingly accepted to be associated with high levels of performance on a range of cognitive tasks (Paris and Winograd, 1990).

Finally, we're interested in conceptualising our investigations within a mathematics education framework. For example, what does mathematics education tell us about young children and their mathematical learning? We know that it is unusual for preschools to conduct formal lessons in mathematics, though one hopes there will be a myriad of practical experiences in which mathematical ideas are fostered. Generally, experiences of this kind are categorised as pre-mathematical in nature, and include measuring, counting and naming, and assisting children gain conventional meanings for a range of ideas and terms essential to later mathematics learning.

We know that by the end of preschool children typically have some number concepts and skills and that these range across a variety of levels. For example, they may see counting as a word game, a number sequence, or sets of numbers, so "(t)hey need a great deal of experience of acting with objects... to reach counting and structuring levels of number" (Leino, 1990, p. 44). Charlesworth (1984) notes that many children start school knowing which of two small groups contains "more", knowing that two objects and three objects make five, can count objects and use the correct number name to ten. These views are consistent with other findings concerning the level of children's counting ability prior to the start of formal schooling (Fuson and Hall, 1983; Gelman and Gallistel, 1978; Ginsburg, 1983; Hiebert, 1986).

One of the problems in early childhood mathematics is that adults often see little difficulty in the learning of pre-mathematical ideas and elementary number work. Baroody (1985), however, emphasises that learning basic number combinations is not "a straightforward, rote memory task". Indeed, learning number combinations is a slow process requiring considerable experience with counting. Importantly, the process is dependent on development of procedures or invented rules as learners gradually replace slow counting procedures with rapid fact retrieval. What these mental representations look like is presently uncertain. But, it appears that learners use more than simple associative models. Indeed, the complexity of human information processing suggests that there may be a series of rules and that they may differ significantly from one learner to the next.

In dealing with the mathematical education of young children it is unfortunate that the majority of early childhood teachers have narrow conceptualisation of mathematics, lack knowledge and experience of mathematics, and know little about processes of mathematics teaching and learning. Burton (1990) believes that in teaching mathematics to young children, and in training early childhood teachers, there is an overly simplistic approach. For example, mathematics is so simplified that it is removed from its relationship to other mathematical ideas and environments. There is also a widespread view that simple mathematics ought to be easy to learn so there is a failure to recognise the highly complex nature of mathematical learning. In a climate where mathematics is viewed largely as a body of concepts and skills for learners to codify and digest there is little recognition that it can or should be a rewarding experience.

The two studies reported here have been conducted with preschool-aged children identified as "at risk" (Elliott, 1991; Elliott and Hall, 1985, 1990 a,b,c; Hall, 1992; Hall and Elliott, 1992). That is, the children are considered "at risk" of early school failure and enrolled in preschool settings that provide early intervention programs aimed at strengthening cognitive and social competence. Given increasing recognition that skilled mathematical problem-solving is dependent on a range of metacognitive activities that are amenable to classroom instruction, our research is concerned with explicating and facilitating metacognitively-rich instructional approaches and examining their effectiveness. Such approaches may be especially important for children experiencing early difficulties with learning (Borkowski, Carr, Rellinger and Pressley, 1990).

STUDY A

The source group for this study was 50 "at risk" preschool children enrolled in early intervention programs. Children were assigned to one of two experimental groups or to a control group, based on assessment scores using the *Test of Early Mathematical Ability* (TEMA 2). Children in the two experimental groups participated in fifteen twenty-minute computer-supported mathematics teaching sessions where they worked in pairs with teacher guidance. Children in Experimental Group 1 participated in a metacognitively-rich mathematical environment based on popular commercial software such as *Number Farm.* Teacher guidance aimed to scaffold cognitive activity by emphasising self-regulatory strategies through questioning and cuing, and modelling and demonstrating aspects of material to be learned. Teaching focus was on extending children's knowledge through broadening and elaborating computer-generated questions and cues, by rectifying discrepancies between the child's response and the ideal situation, through minimising frustration and encouraging risk in problem solving, and by demonstrating an idealised version of the problem's solution. In Experimental Group 2 the teaching emphasis was on informal, caring and supportive teaching much like that normally used in the preschool. Children in the third group, the control group, did not participate in any computer-supported mathematics activities. All children continued to engage in the usual range of informal preschool experiences designed to engender mathematical activity, such as sand, water and block play. The TEMA 2 instrument was used to measure mathematical achievement after the completion of the intervention program.

An example of the interaction generated in the metacognitive teaching session is shown in Table 1 below where a teacher is talking to two children (C_1 and C_2).

In the metacognitive teaching approach adult mediation serves to focus the child's activity on the task at hand, to encourage planning, regulation and evaluation of performance in each task, and to link new information with present knowledge. The cognitive consequence of this learning is that children become enable to select and attack problems strategically (Paris and Winograd, 1990) and to develop rich conceptual networks. Engagement in intellectual activity that exercises and stretches thinking processes is dependent on the interactivity generated by the learners and adults, as well as the computer and software. As we all well know computers do not in themselves generate cognitive activity that results in learning (de Corte, 1990; Elliott and Hall, 1985; Pea, 1987; Salomon, 1990).

Teaching activities selected by either the computer or the teacher included counting a variety of objects, either right to left or left to right, but discouraging random selection because of errors that would follow, drawing objects then counting them, finding then typing the numeral on the computer keyboard, representing the set, and writing numerals. These activities are consistent with, though not as comprehensive as the approaches reported by Saxe, Becker, Sadeghpour and Sicilian (1989) where the researchers gave emphasis not only to one-to-one correspondence, to the last element as the number representing that set, and to counting, but to the arbitrary nature of the conventional names and symbols used in counting. Our teaching activities are also consistent with Steffe, von Glasersfeld, Richards and Cobb's (1983) perceptual, figural, motor and verbal conceptual structures of number development. That is, in Steffe et al's terms, the activities encouraged using representations to count in order to begin counting at one, to re-present a collection of objects, and to re-present a counting activity. And our approach is consistent too, with Greeno, Riley and Gelman (1984) who had children create sets of objects, count them and find the correct numeral to represent them, so as to increase the likelihood that learners would associate the number of objects counted with its numeral representation. They claimed that young children's counting was far more than rote recitation. Rather, it reflected understanding of counting principles including cardinality, one-to-one correspondence and order.

Table 1: **An extract from dialogue during the metacognitive teaching approach**

Four objects on the computer screen.
T: How many have we got here?
C_1: (Points with finger on screen, and counts)
One, two, three, four.
T: (Asks second child)
How many do you think there are?
C_2: Four.
T: Well, can you show me four fingers?
C_2: (Holds up four fingers, counts)
One, two, three, four.
T: How old are you C_1?
(C_1 shows four fingers)
How many is that?
C_1: Four.
T: How many candles did C_1 have on her tray?
C_2: Four
T: How many eyes have you and C_2 got together?
C_1: Four.
T: How many hands have you and C_1 got together?
C_2: Four.
T: How many ears have you and C_1 got together?
C_2: Four.

RESULTS A

Analysis of variance procedures showed significant differences in mathematical gain scores between the three groups ($p < .001$), with the control group performing least well. Further analyses showed that the gains made by the metacognitive teaching group were significantly higher than those of the non-metacognitive teaching group ($p < .01$), and that the comparison group made no significant gains in mathematics scores during the period of the research.

We suggest, then, that computer mediated learning environments are successful in helping "at risk" preschoolers learn pre-mathematical and arithmetic concepts and skills. Further, we contend that our metacognitive teaching approach encourages greater mathematical learning than a typical caring, concerned teaching approach even when that approach was embedded in an interactive computer-supported setting. That children in the control group did not improve their mathematics achievement scores over the research period is cause for concern. It would seem there are too few informal mathematical experiences provided by the preschools. Given that the children in the study were already exhibiting signs that early mathematical learning was not proceeding as well as might be expected, it is important that opportunities be provided to strengthen these children's mathematics learning.

STUDY B

The success of the computer-supported metacognitive approach and concern for the overall quality of mathematics curriculums for "at risk" preschoolers led to further research and program development in one of the preschools. During the period of this second study the preschool revised its mathematics program, so that it went from exclusively unstructured mathematical play experiences, to one in which mathematical activities were more regularly included in the curriculum, supported by a mathematics corner and by newly purchased mathematical materials. There was also a more conscious effort to intervene so as to draw out the mathematical aspects of all free-play and guided learning settings. Further, the teachers adopted the metacognitive teaching approach described above, both in the computer context as well as in the broader activities of their teaching program.

Each child's concepts and skills in mathematics were assessed using the TEMA 2 test at the start of the research period, and were reassessed six months later. All 24 children in the class, most of whom were "at risk", were assigned to one of two groups based on their pretest scores. Both groups of children experienced computer-mediated learning for fifteen twenty-minute sessions during the six months. Teaching in the experimental group emphasised mathematical learning experiences of the kind described as the metacognitive teaching approach in Study A. The comparison group's computer experiences were non-arithmetical, generally language and drawing programs. This experimental design allowed us to see if changes to the preschool's mathematics program had led to improvements in children's mathematical learning, to contrast gains of the experimental group with gains of the comparison group, and to see if a less intensive computer experience, than implemented in Study A, would still lead to gains in mathematics scores.

RESULTS B

An analysis of variance of the gain scores for the two groups showed a significant difference ($p < .01$) favouring the group with additional mathematical experiences. Further analyses showed the comparison group's gains to be significant at the .05 level, thus indicating that the preschool's revised mathematics program was having an impact on children's mathematical learnings.

These results indicate the cognitive benefits of a more focussed and metacognitively-rich pre-mathematical and mathematical program. Additionally, they suggest that even when a preschool's mathematics program is improved, it is likely that children can gain further through experiences within computer-mediated contexts. We know, too, that these gains can be achieved through a modest investment in computer and human resource time; in this research children had computer access for less than twenty minutes per week.

CONCLUSIONS

Findings from the studies reported above suggest the effectiveness of interactive, metacognitively-rich computer environments for enhancing "at risk" preschoolers' mathematical learning. That is, children's gains in mathematical achievement are greater in computer-mediated environments, even when more traditional environments are metacognitively enriched. The validity of teaching those concepts and skills that formed the subject matter of our research, at the preschool level is, however, debatable, and our answer is very pragmatic. We accept Cobb's point concerning emergent mathematical meanings and institutionalised mathematical knowledge (1990), and note high teacher, parent, pupil and broader community expectations of children in the first years of school, especially as they concern learning arithmetic. In our opinion, these expectations mean that for many "at risk" children, early mathematical disadvantages are magnified so that they fall further and further behind their peers, and so move further and further away from the goal of institutionalised mathematical knowledge. So the gap between mathematically competent children and those struggling to learn concepts and skills grows from the very beginning of school.

The metacognitive teaching approach adopted in these studies, especially when embedded in an interactive computer context seemed to provide a valuable scaffolding for the development of cognitive competence in mathematics. Importantly, it encouraged planning, reflection and evaluation as children constructed their own knowledge (Steffe and Wood, 1990; von Glasersfeld, 1991). The interactivity within the computer environments seemed to allow for more cognitive conflict and re-construction than was the case without computer intervention

In our continuing research in this area we are focussing on refining the metacognitive model, particularly in respect of those contextual supports most effective in maximising metacognitive activity. First though, we need to ascertain exactly which contextual supports are most effective in maximising academic competence, and then determine the most effective ways of designing environments to enhance the benefits of these supports. Further research is also required to examine the impact of enriched mathematical preschool experiences on children's first years of school. Additionally, we need to consider the professional development of teachers, the appropriate content of preschool mathematics programs, and the specifications of computer software.

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