Technology-supported Learning: Critical Analysis and Future Perspectives

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The introduction of computers in schools in the early 1980s was accompanied by high expectations concerning the potential of the New Information Technology (NIT) for improving education. However, at present it has become clear that those expectations have not been fulfilled, neither by computer-assisted instruction nor by intelligent tutoring systems. It is argued that this is largely due to the educationally inadequate conditions of computer applications in classrooms, based on unrealistic assumptions about the instructional potential of the NIT and on an inappropriate conception of learning as a passive process of information absorption. A new expanding conception of productive educational computing is described: computers should be embedded in powerful collaborative learning environments as tools that elicit and support in students active processes of knowledge acquisition, meaning construction, and problem solving. Two representative examples of educational software that are in line with this conception are discussed. Finally, suggestions for further research and development work as well as some recommendations for a supporting policy are presented.

La introducción de los computadores en las escuelas a comienzos de los años 1980, fue acompañada por altas expectativas en relación al potencial de la Nueva Tecnología de la Información (NTI) para mejorar la educación. Sin embargo, en este momento, ha quedado en claro que esas expectativas no se han cumplido, ni por la instrucción asistida por computador, ni por los sistemas tutoriales inteligentes. Se argumenta que esto se debe, en gran parte, a las condiciones educacionales inadecuadas de las aplicaciones del computador en las aulas, basadas en supuestos poco realistas sobre el potencial instruccional de las NTI y en una inadecuada concepción del aprendizaje como un proceso pasivo de absorción de información. Se describe una nueva concepción comprehensiva de la computación educacional productiva: los computadores debieran estar insertos en ambientes de aprendizaje colaborativos en forma de herramientas que hacen surgir y que apoyan procesos activos de adquisición de conocimientos de los estudiantes, así como construcción de significados y resolución de problemas. Se analizan dos ejemplos representativos de software educacional que están en consonancia con esta concepción. Finalmente, se presentan sugerencias para ulterior investigación y trabajos posteriores, así como recomendaciones para una política de apoyo.

1. High expectations not redeemed

When microcomputers began to be introduced in schools in the early 1980s, it was predicted that this new interactive and dynamic medium would significantly change the quality and the outcomes of schooling, even before the end of the decade. Today –about ten years later– there is robust evidence showing that the predictions have not come true, and were probably more based on wishful thinking than on well-grounded arguments.

For example, Becker (1991) reported the U.S. data for a major survey about the use of computers in education carried out in 21 countries by the International Association for the Evaluation of Educational Achievement (I.E.A.). While the number of computers available in American schools has increased strongly between 1985 and 1989 –from the average of 4 to 17 in elementary schools, and from 16 to 39 in high schools– Becker comes nevertheless to the conclusion that "only a small minority of teachers and students can be said to yet be major computer users –where a large portion of instruction, learning, or productive work in one class is being accomplished through the use of computers" (pp. 405-406). There are no reasons to believe that this situation is different in other countries.

As far as learning outcomes are concerned, the well-designed studies report few and very modest significant results in favor of computer-assisted instruction (CAI) in comparison to traditional classroom teaching (Krendl & Lieberman, 1988). And, in an investigation involving 339 students from fourth to tenth grade classes, Krendl and Broihier (1992) recently found evidence supporting the view that positive results of computer application in schools might be short-term novelty effects. Indeed, they observed that over a three year period students' preference for or enjoyment of computers as well as their perception of the instructional effectiveness of the technology declined significantly over time. On the other hand, students perception of the difficulty of using computers did no decrease.

All these findings show obviously that the initial expectations with respect to the short-term impact of the New Information

Technology on schooling ran too high. This is also confirmed by Kaput's (1992) recent description of the state-of-the-art in the domain where one would have anticipated the most significant breakthrough of the computer, namely mathematics education:

1. Notwithstanding the increase over the past years, it is still so that only very few and mostly obsolete computers are available in schools.

2. There is still a lack of software in sufficient quantity and of sufficient quality to warrant the investment necessary for large-scale computer use.

3. Computers are too difficult for the average teacher to use in the typical classroom on a sustained basis (among others because the available software is not sufficiently tied to and certainly not integrated in the school curriculum).

4. Pre-service teacher training falls short in providing future teachers systematic in-depth experience with computers.

5. Because of the preceding circumstances teachers have only very low, if any at all, expectations concerning computer support for their teaching.

If there is anything to be surprised about it is certainly not this state-of-the-art, but rather the unrealistic expectations of the early 1980s. Indeed, it seems that the history (of educational technology) repeats itself, and that we do not learn too much from it. Take, for instance, the following claim quoted by Cuban (1986):

> "The central and dominant aim of education by (computers) is to bring the world to the classroom, to make universally available the services of the best teachers... The time may come when a [computer] will be as common in a classroom as a blackboard. [Computer] instruction will be integrated into school life as an accepted educational medium." (p. 19)

This statement echoes many similar ones heard in the 1980s; only this one dates from 1932 and relates to the educational use of the radio!

On this respect, it should be added, that overlooking the unredeemed expectations of previous educational gadgets does not only hold true for their short-term impact on educational practice. Indeed, educational computing research has –certainly initially– also replicated the naïveté and the errors of the work done in the past with respect to other media (Lowyck & De Corte, 1986; Salomon & Gardner, 1986). But meanwhile things have changed in the researchcommunity as will be illustrated later on (see De Corte, Linn, Mandl, & Verschaffel, 1992).

2. What's wrong with current computer applications in education?

A major cause of the relative failure of educational computing – as well as of previous "latest novelties" in the instructional technology toolbox– is that the computer has been mainly introduced as an *add-on to an existing and unchanged classroom setting* (see also Salomon, 1992; Schank & Jona, 1991). In mathematics, for instance, the large majority of the available software fits into the category of drill-and-practice programs, and aims mainly at exercising computational skills replacing in this respect traditional worksheets (Kaput, 1992). This means that the New Information Technology is implemented to reproduce and preserve the status quo. However, this existing practice of mathematics education has itself been heavily criticized over the last ten to fifteen years. As a result major efforts are done to transform mathematics learning and teaching from the individual absorption and memorization of a fixed body of decontextualized concepts and procedural skills transmitted by the teacher, into the collaborative, teacher-mediated construction of meaningful and useful knowledge and problem-solving skills based on mathematical modelling of authentic, real-life situations and contexts (see De Corte, Greer, & Verschaffel, in press: NCTM. 1989).

The situation in other subject-matter domains does not seem to be much different. In language teaching, for example, programs focusing on practising rules of spelling and grammar also prevail, and much less software is available that supports the more essential aspects of reading and writing, namely comprehension and communication. As Becker's (1991) report of the I.E.A. data for the U.S. illustrates, there is a tendency since the late 1980s that word processing emerges as a major computer-based activity at the highschool level. However, a further analysis indicates that the focus is on how to use a word processor rather than on improving students' skill in expressing their ideas through writing.

It has now become obvious that the mere add-on strategy of computer use in schools can not produce the improvements in the quality and the outcomes of learning that were originally anticipated. A partial explanation of the inefficacy of this strategy is that the prevailing drill-and-practice applications only elicit in students lowerlevel mental activity, and do not at all exploit the specific potential of the computer such as its interactive possibilities and its tremendous capacity for data presentation and handling (see e.g. Makrakis, 1988).

A more fundamental reason, however, for the failure of the add-on strategy is that it is based on a wrong assumption, namely that computers will evoke by themselves productive learning. The most typical illustration in this respect relates to the way that Logo has often been used referring to Papert (1980): it was expected that "mindstorms" resulting in improved thinking and problem-solving skills, would rise of themselves in children's heads due to the unique characteristic of the Logo environment. Contradicted convincingly by well-designed studies as well as by practical experience this viewpoint has meanwhile been abandoned. But the most implicit assumption that computers can by themselves elicit and facilitate student learning, brings us to an ongoing debate in the current literature, namely whether computers have unique effects on the acquisition of knowledge, skills, and beliefs. In this respect, an extreme negative position has been taken by Clark (1983) who claims that

> "...media are mere vehicles that deliver instruction but do not influence student achievement any more than the truck that delivers our groceries causes changes in our nutrition." (p. 445)

According to Clark, the method and the content of instruction are the critical factors in producing learning effects, albeit that the medium can influence the efficiency and the cost of delivering instruction. In other words, the potential of the computer lies in some economic benefits, not in learning benefits (see also Clark, 1992).

Based on an extensive review of the literature on learning with media, Kozma (1991) has contested Clark's view. Specifically with respect to computers, he reviewed studies that show how the transformation capabilities on the machine help students in an effective way to build links between the symbolic expressions of graphs and the corresponding real world phenomena; other work in physics demonstrates how learners develop more consistent and accurate mental models of phenomena through manipulation of symbolic representations of formal constructs in computer microworlds. Taking these findings into account, Kozma argues that, in a good instructional design, media and method are narrowly integrated, and, consequently, that the learner constructs knowledge in interaction with medium and method.

Considering the available evidence and the arguments involved in the ongoing dispute, I take –in line with Kozma's position– the point of view that the productive educational application of computers requires that they are *embedded in powerful teaching-learning environments,* i.e. instructional settings that elicit in students the acquisition processes necessary to attain worthwhile and desirable educational objectives. Embedding means here that the computer is not just an add-on, but is judiciously integrated in the environment capitalizing on its specific strengths and potential to present, represent, and transform information (e.g. simulations of phenomena and processes), and to induce effective forms of interaction and cooperation (e.g., through exchanging data, information and problems via a network).

3. Intelligent tutoring systems: THE solution?

Paralleling the large-scale introduction of computers in education, the cognitive science community interested in learning and teaching has invested a lot of work and effort in the design of intelligent tutoring systems (ITS) (for an overview see Goodyear, 1991; Sleeman & Brown, 1982; Wenger, 1987). It is interesting to ask the question whether this interdisciplinary research endeavour has yielded results in view of remediation of the failures of educational computing. This question forces itself because a major incentive for designing ITS derived from dissatisfaction with traditional computer-assisted instruction (CAI) that prevailed and still prevails in educational practice. In fact, educational software involving artificial intelligence (AI) was originally called "intelligent" computer-assisted instruction (ICAI). The critical distinction between CAI and ITS is that CAI are static systems that embody the decisions of expert teachers, while ITS contain expertise itself and can use it as a basis for taking decisions about instructional interventions. The domain of AI and education is an interdisciplinary crossroad, and, consequently, the development of intelligent tutors is guided by a substantial and varied body of inquiry-based knowledge. Nevertheless the field is strewn with pitfalls.

For instance, one very robust result of research on learning and instruction is that student's prior knowledge is a very strong determinant of their future learning (see e.g. Dochy, 1992). Therefore, instruction should explicitly be linked up to prior knowledge, and the ITS community has taken this principle seriously. Indeed, a major component of an intelligent tutor is the student model which, as Wenger (1987) states:

> "...should include all the aspects of the student's behavior and knowledge that have repercussions for his performance and learning." (p. 16)

But the same author adds immediately that building such a student model is a very difficult task for computer-based systems. Moreover, it is by now not clear how far one should go in the construction of student models, and how flexible and diagnostic a system should be in view of providing the most appropriate guidance. Putnam (1987), for instance, tested the idea that a detailed model for a student's knowledge is a prerequisite to successful remediation. He found no support for the so-called diagnostic-remedial model: experienced teachers did not try to construct detailed models of children's wrong procedures as a basis for remedial instruction.

An even more fundamental issue concerns the nature of the guidance that an ITS should provide taking into account the now well-documented conception that learning is an active and constructive process: learners are not passive receptacles of information, but they actively construct their knowledge and skills through interaction with the environment and trough reorganization of their prior mental structures (Cobb, in press). Consequently, as argued by Scardamalia, Bereiter, McLean, Swallow, and Woodruff (1989), computer-based learning environments should support the constructive acquisition processes in students. The question raises whether the existing ITS are in accordance with this constructivist view of learning. Indeed, "traditional" intelligent tutors that base their instructional decisions on a detailed diagnosis of student's knowledge, can easily led to a preponderance of highly structured and directive learning situations lacking sufficient opportunities for active learner involvement and participation. Anderson's *Geometry Tutor* (Anderson, Boyle, & Reiser, 1985), one of the most frequently quoted examples of an ITS, is an illustration of such a directive system. As remarked by Kaput (1992), suggested attempts to make the tutor more flexible and educationally adjustable will not change its underlying epistemology: "the knowledge and the underlying authority of the tutor reside in the computer." (p. 545) Paraphrasing Papert (1990) who opposes "constructionism" to "instructionism", one could say that the Geometry Tutor will continue to reflect an "instructivist" rather than a "constructivist" view of learning.

The now prevailing constructivist conception of learning and the problems confronting the design of ITS, have fostered the emergence of the view that computer-based learning environments should not so much involve the knowledge and intelligence to guide and structure learning processes, but that they should rather create situations and offer tools that stimulate students to make maximum use of their own cognitive potential (Scardamalia et al., 1989). In this connection Kintsch (1991) has launched the idea of *unintelligent tutoring:*

> "A tutor should not provide the intelligence to guide learning, it should not to the planning and monitoring of the student's progress, because those are the very activities the students must perform themselves in order to learn. What a tutor should do is to provide a temporary support for learners that allows them to perform at a level just beyond their current ability level." (p. 245)

It is obvious that Vygotsky's (1978) notion of the zone of proximal development underlies this view about the optimum nature of the interventions to support constructive learning processes.

In line with this evolving concept of computer-based learning (see also Brown, 1990), there is a clear shift toward supportive systems that are less structured and less directive, that are more focusing on coaching than on tutoring, that involve student-controlled tools for the acquisition of knowledge, and that attempt to integrate both, tools and coaching strategies, in collaborative learning environments (see also Kaput, 1992). In those environments the New Information Technology is not anymore just an add-on, but is embedded in the sense as expressed in the previous section. Furthermore, they aim at the elicitation of constructive acquisition processes, and make ample use of student interaction and cooperative learning (for a discussion of recent research on cooperative learning with computers see Mevarech & Light, 1992). Development work and investigations relating to such environments, based on the available knowledge accumulated in the domain of research on learning and instruction, can contribute to realize gradually the aspirations expressed by Kolodner (1991) in her editorial statement in the first issue of *The Journal of the Learning Sciences:*

> "But rather than trying to use computers to solve all of education's problems, we need concrete guidelines about what kinds of educational environments are effective in what kinds of situations, and based on those guidelines, we need to develop more innovative ways to use computers." (p. 2)

In the next section a representative example of a powerful computer-based learning environment will be presented.

4. Computer-Supported Intentional Learning Environments (CSILE)

Embedding computers in powerful learning environments involves that they are applied to pursue and achieve worthwhile educational objectives. Research on learning and instruction over the past ten to fifteen years has contributed to rethinking the objectives of schooling. As a result more emphasis is put today in the cognitive domain on understanding, problem-solving skills, metacognitive strategies, and learning to learn as opposed to the acquisition of memorized knowledge and low-level procedural skills. The CSILE project focuses on fostering those higher-order cognitive activities in students, especially learning to learn. Indeed, the term *intentional learning* refers to cognitive processes that have learning as a goal (Bereiter & Scardamalia, 1989). The expression "computer-supported intentional learning environments" is used by Scardamalia et al. (1989) as a general term defined as follows:

> "...environments that foster rather than presuppose the ability of students to exert control over their own learning." (p. 52)

The acronym CSILE refers then to particular environment which the authors have developed.

Background of CSILE: Procedural facilitation of writing

CSILE has grown out of research by Scardamalia, Bereiter and their co-workers in the mid-1980s on the learning and teaching of writing. A starting point of their work were findings showing important differences between expert writers and novices. Children who are novices usually start writing immediately down what they know about an assigned topic (knowledge-telling approach). In contrast skilled writers invest much more time in planning and revising their text; as a consequence, they engage in a knowledge-transforming process, involving goal setting and problem solving besides generating of the text as such.

On the basis of a detailed analysis of the writing activities of experts Scardamalia, Bereiter, and Steinbach (1984) developed a procedure, called *procedural facilitation,* aiming at fostering students' metacognitive activities during writing. The procedure consists in providing computer support in the form of planning and revising prompts presented as open sentences (e.g., "A better argument would be...") to guide the writing process. This is in line with the basic idea put forward in the preceding section, that the computer environment should present tools that stimulate students to exploit their own cognitive potential. In Vygotskian (1978) terms one can say that procedural facilitation acts as a scaffold in the learner's zone of proximal development which will progressively be transformed into actual development through internalization of the procedure; as a consequence students become more and more autonomous and can take responsibility for their own learning. Scardamalia et al. (1984) have shown that the application of procedural facilitation has a favorable impact on children's planfulness and reflectivity during writing and on the quality of their texts.

Design principles and architecture of CSILE

On the basis of this initial work Scardamalia & Bereiter (1991; 1992) have expanded and elaborated their system into a more general computer-based learning environment, that does not focus on a particular subject but aims at penetrating and affecting the whole curriculum. Technically speaking, CSILE is a networked hypermedia system allowing students to construct their own, common database consisting of text and graphical material; all students have access to the database, and they can comment on each others notes. This latter basic feature of the system aims at inducing collaborative knowledge construction in the classroom. The following seven design principles underlying the latest version of CSILE intend precisely to facilitate the development of such a knowledge-building community (see Scardamalia & Bereiter, 1992 for a more detailed discussion).

1. Objectification: the system should help learners to treat knowledge as an object that can be discussed, criticized, changed, related to other knowledge,...

2. Progress: constructing knowledge within the system should yield perceptible progress for the learners.

3. Synthesis: the system should stimulate and facilitate knowledge integration as well as higher-order representations.

4. Consequence: the system should ensure that each leaner gets informed about the outcomes of his contributions (e.g., use of one's ideas, comments on one's notes).

5. Contribution: the system should help learners to see how they contribute to the progress of the group's knowledge.

6. Cross-fertilization: the system should maximize chances to discover interesting and useful related information.

7. Sociality: the system should be embedded in and help to integrate the intellectual and social life of the classroom.

An architecture for CSILE is developed to support these design principles in view of the facilitation of the conscious, collaborative construction of shared knowledge in the classroom. The five main components of this knowledge-building architecture are: the community database, knowledge-building environments, thematic spaces, tools and procedural facilitations, and background operations. Space restrictions do not allow to elaborate all these components in some detail. Therefore, only a few major points will be briefly discussed (see again Scardamalia & Bereiter, 1992, for additional information).

The community database involves all the knowledge in the system in the form of user-generated notes. A major characteristic of the new version of CSILE concerns the differentiation of the database along two dimensions: 1) knowledge-building environments representing and fostering different knowledge operations (e.g., the EXPLANATION environment supporting the search for coherent explanations of some facts and the testing of the explanatory power of the hypotheses; the HOW-IT-WORKS environment to identify and work out causal mechanisms; the MEANING environment supporting the extraction of domain vocabulary from students' notes and the construction of a network of terms in a thematic space); 2) thematic spaces representing different topics and substantive domains involved in the database (e.g., fossil fuels, smoking and health, developments in Eastern and Central Europe). Both dimensions –knowledge-building environments and thematic spaces– should be considered as intersecting; for instance, working in the "smoking and health" space students may want to find out why smoking causes oftentimes coughing, and therefore, move from the undifferentiated HOME environment to the HOW-IT-WORKS environment.

Procedural facilitation, developed originally with respect to supporting students' writing processes as described above, is selectively used in the latest CSILE-version, namely to stimulate learners to come up with more interesting notes than they produce spontaneously (e.g. "My hypothesis is different from yours. I think..."), and to support students in thinking more thoroughly and effectively about the content of their own notes. Background operations are automatically executed without intervention of the learner; one important example is providing students with information about related notes of interest on the basis of an automatic screening of the database. Finally, I mention that it is also the intention to create the possibility of importing in the system reference material from other media such as video, microworlds, CD-ROM, etc.

Initial research results

While the latest version of CSILE is still under development, some promising results have already been obtained with the initial version of the system. Working with students of grades five and six in a first school try out, Scardamalia et al. (1989) observed that:

> "Students used the system to elaborate models and hypotheses, to delve into difficult texts, to seek deeper levels of explanation, to elaborate confusions, and generally to engage in processes thought to be beyond their years." (p. 65)

A more systematic study in two grade 5-6 classes (Scardamalia & Bereiter, 1991) showed that children in the CSILE-environment can generate educationally productive or knowledge-building questions, i.e. valuable questions to guide further learning on a topic because their investigation involves the potential to advance substantially one's knowledge and understanding. Being able to ask this kind of questions –as opposed to pure text-based questions– is considered as an indication that children can take control over and responsibility for their own learning. With respect to two topics which differed in terms of the amount of children's prior knowledge –endangered species and fossil fuels– a significant number (46%) of knowledge-building questions were generated (e.g. When an animal is endangered, how does it make a comeback? Does fossil fuel affect the ozone layer?).

The same study also demonstrated how cooperative knowledge construction is supported in the CSILE environment. In this respect, CSILE allows for another form of cooperation than face-to-face (small) group work, namely cooperation through commenting on or using information from notes of other learners. For instance, a student can ask a question relating to a note of another pupil, refer to additional data sources, express a critical comment, etc. Observations are reported which indicate that even weaker students can produce relevant questions and helpful comments leading to more thorough examination, and, consequently, deeper understanding of the topic under study. Other data illustrate how students collaboratively elaborate a topic (e.g., fossil fuels) by producing a network of charts showing the different uses of fuels in the kitchen. The result involves, for example, a chart relating to wrapped food accompanied by the following comment: "The wrapping on this bowl of chili is made of plastic. Plastic comes from petroleum. Plastic causes a lot of pollution. Wax paper is much better for the environment." (Scardamalia & Bereiter, 1991, p. 65).

Similar promising results have been obtained in other projects that aim at restructuring whole classroom environments on the basis of the same underlying conception of learning as a constructive and distributed activity (see e.g., De Corte et al. 1992). A major related project is the work of Brown, Campione, and their colleagues (Brown, Ash, Rutherford, Nakagawa, Gordon, & Campione, in press; Campione, Brown, & Jay, 1992). Integration of the technology in those environments is not only attended with an alteration in the position and the contribution of the learner, but also with fundamental changes in the role of the teacher. Instead of being the only source of information and having full control over the teaching-learning process, the teacher becomes a "privileged" member of the knowledge-building community, who creates an intellectually stimulating climate in the classroom, models learning and problem-solving activities, asks provoking questions, provides support to students through coaching and scaffolding, and fosters students' control over and responsibility for their own learning (see also Scardamalia &

Bereiter, 1991). This does not at all exclude the use of direct teaching, but it occurs rather –as expressed by Campione et al. (1992)– on a "need to know" basis.

5. The Geometric Supposers: A tool for learning and problem solving in mathematics

The computational component of CSILE is a domain-independent hypermedia system that can be used as an educational medium throughout the curriculum. But, there is also a need for *domain-specific* tools for learning and problem solving around which powerful instructional environments can be built guided by the same basic principles and guidelines. While there have so far not been many efforts in that direction, a number of examples have emerged since the late 1980s. A good example of such a tool are the *Geometric Supposers* developed by Schwartz and Yerushalmy (1985, 1987).

The Geometric Supposers are a series of computer programs that create a powerful learning environment in which students become active learners and explorers of Euclidean geometry guided by their teacher. The underlying ideas are that students can make their own mathematics, and that formulating and testing conjectures constitute the main activities of doing mathematics. The Supposers elicit and facilitate such activities by offering a tool for constructing, manipulating and exploring geometric shapes.

The menu-driven programs allow students to choose a primitive shape (e.g., a triangle) on which they can easily make constructions (e.g., a median) by giving the necessary specifications in formal geometric language (e.g., the vertex from which the median should be drawn). The program also allows easy measurements of a drawing as well as their recording. An important aspect of the Supposers is the "Repeat" option: the program captures the constructions carried out on a shape as procedures, that can be repeated afterwards on other similar figures. The importance of this option, apart from freeing the learner from the burden of making the drawings, can be illustrated by the following example (see Yerushalmy Chazan, 1990, p. 205). After observing that the three medians in a particular triangle intersect in one point, the learner can easily verify whether this is a typical characteristic of this triangle, or whether it holds for some or for all triangles. Stated in more general terms a basic feature of the Supposers is that they make it easily possible to explore the effects of one's construction across a set of equivalent figures, and, thereby, to test conjectures and hypotheses about geometric shapes on the basis of large amounts of visual information, and to look for invariants in geometric constructions. *Cabri Géométrie,* a program developed in Grenoble, France (Baulac, Bellemain, & Laborde, 1988), offers the same possibilities, although implemented in a somewhat different way. The major difference with the Supposers is that Cabri does not have the "repeat" option; but this allows also the easy modification of shapes by moving actions on certain parts of a figure. For example, the shape of a triangle can be changed by dragging a vertex; all the other parts (the other vertexes, the sides, but also the medians...) will move simultaneously and be in the correct position in the new triangle.

Several studies (see e.g., Yerushalmy, 1991; Yerushalmy & Chazan, 1990) have already shown that, when used as intended, the Supposers create indeed a new and powerful learning environment: traditional geometry lessons in which students absorb passively definitions, propositions, and theorems developed by other people are transformed into active and collaborative explorations of geometrical shapes resulting in stating, testing, and proving one's own conjectures. In line with a basic idea underlying this presentation, this activity of the learners is guided by the teacher. Indeed, the Supposers do not stand alone , but are

> "part of an approach to teaching geometry that is used by teachers as they see fit and that includes problems and projects for students. The student's work with the software is a part of the course, not the whole. Therefore, as important or even more important than the software itself is how its use is integrated into the course and how teachers make use of the capabilities the software provides". (Yerushalmy & Chazan, 1990, p. 206)

The appropriate embedded use of the Supposers presumes a radical shift in teachers and students conception of mathematics from something that learners encounter and observe to something they do and invent (Kaput, 1992). Moreover, it is quite demanding for both teachers and students, requiring substantial teacher planning and continuous effort from the former and assuming to a large degree responsibility for their own learning from the latter. The instructional approach used by Yerushalmy and their colleagues is a form of so-called inquiry teaching, involving that teachers create and provide real and stimulating problems which evoke exploratory activities and inquiry experiences in students working often in pairs (Yerushalmy, Chazan, & Gordon, 1990). Stating such problems is not an easy task, because they should at the same time be sufficiently clear for students and leave room for exploration and creativity. In other words, and in line with the conception of computer-supported powerful learning environments outlined earlier (see section 3), in posing problems and also in guiding students explorations one should find the right balance between systematic instruction and discovery learning.

The investigations referred to above as well as other studies have also shown that the Supposers-supported geometry learning environments yield promising learning outcomes in secondary school students. For example, at the end of a one-year teaching experiment Yerushalmy (1991) found that 46 eight graders who worked with the Supposers outperformed a comparison group of 99 students on a test measuring knowledge of basic geometric concepts. The comparison group was taught the same concepts and topics during the same amount of time, but in the conventional way. A main difference between both groups was that the experimental group did not exhibit some of the frequently observed, persistent misconceptions such as having a stereotyped image of certain geometrical concepts and shapes. In another study Yerushalmy & Chazan (1990) demonstrated that working with the Supposer fosters high-school students' visual flexibility; indeed, they seem to overcome more easily frequently occurring visual obstacles in interpreting figures and diagrams such as the particularity of diagrams and the inability to perceive a diagram in different ways. An important last finding to be mentioned was reported by Kaput (in press): Supposer experience influences substantially students' beliefs and attitudes about mathematics.

In summary, the Supposers –and *Cabri Géométrie* as well– are excellent, but still too rare examples of what Kaput (1992) has recently called "implementing technology toward reformed objectives" (p. 548). These programs are very much in accordance with a number of guidelines for the design of good computer-supported learning environments discussed above: they stimulate active learning oriented toward higher-order cognitive skills in a collaborative and teacher-guided context, and they exploit optimally the computers interactive potential as well as its capacity to present and manipulate graphic and symbolic information.

6. Summary, conclusions, and perspectives

Neither traditional computer-assisted instruction nor intelligent tutoring systems have been able to fulfil the initial high expectations, that rose in the early 1980s with regard to the potential of computers to improve substantially the quality and the outcomes of learning and instructions. A critical examination of those prevailing educational computer applications, based on the findings of media research and on our present understanding of the nature of productive learning processes, has shown that this is not at all surprising. Indeed, underlying many current educational uses of computers –albeit often implicitly– is the wrong assumption that computers will by themselves elicit "good" learning, as well as a conception of learning as a rather passive and highly individual process of knowledge absorption and accumulation. This is in contrast with the new conceptions about the productive educational use of computers that has evolved over the past years: computers should be better integrated in the curriculum and embedded in powerful reaching-learning environments as tools that elicit and support in students, in interaction and collaboration with the teacher, fellow-learners and other instructional media, active processes of knowledge acquisition and meaning construction. CSILE, a domain-independent hypermedia system usable throughout the curriculum, and the Geometric Supposers, a series of domain-specific tools for geometry learning, have been discussed as examples of good instructional software that are in line with this new view of productive educational computing.

Other illustrations can be found in the recent literature. In our own work, for instance, we are developing a new Logo-based learning environment. In contrast to the original discovery approach to learning Logo, it has built-in tools supporting the acquisition of planning and debugging skills and contains a computer coach providing comments and orienting help based on an analysis of pupils' activities. Nevertheless the students remain in control and take responsibility for their own learning; indeed, use of the supporting tools and of the coach's guidance is optional and can also be gradually removed. Notwithstanding the availability of a lot of built-in help, the system is intended to operate in a teacher-mediated environment; utilizing the tools and the coach gives the teacher more opportunity for guidance and interventions focusing on the elicitation of problem solving and reflective activities in students (De Corte, Verschaffel, Schrooten, Olivie, & Vansina, in press).

Those examples and prototypes of software programs that embody the more recent ideas of good educational computing set at the same time the trend for future inquiry and development at the intersection of artificial intelligence, cognitive science, educational technology, and research on learning and instruction. Indeed, we are only at the beginning of what may become a new era in educational computing, and the further elaboration and testing of research-based principles for the design of powerful computer-supported learning environments is a challenging, joint task for scholars in the fields just mentioned and interested expert-practitioners. But there is, in addition, also a strong need for continued theory-oriented research aiming at a better understanding and fine-grained analysis of the constructive learning processes that this new type of learning environments evoke in students, of the precise nature of the knowledge, skills, attitudes and beliefs they acquire, and for the critical dimensions (e.g., the balance between discovery and exploration, on the one hand, and guidance and mediation, on the other) that can account for the power and efficacy of these environments.

Finally, it is obvious that the changed view of learning supported by informatics has implications for the policy with respect to educational computing. Without trying to be exhaustive, a first issue relates to a possible re-allocation of the resources for research and development in order to stimulate projects along the lines suggested above. A specific recommendation in this regard is to promote socalled design experiments (Collins, 1992, see also Brown, in press) in which researchers, in narrow collaboration with practitioners, construct and evaluate innovative teaching-learning environments, and, at the same time, use these environments as a "work-bench" for doing theory-oriented research. A second important issue concerns the reconsideration of pre-service and the in-service training of teachers with respect to the instructional use of computers. Teachers should not only become acquainted with the changing conceptions of educational computing, but they should also be actively trained in the application of new software tools and programs in their teaching. A specific recommendation in this connection is to incorporate in teacher training programs classrooms where design experiments are conducted, as prototypical contexts for learning through modeling and as starting points for further implementation and dissemination of powerful computer-supported learning environments.

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