The research corpus on the use of computer environments for enhancing children’s metacognition is incomplete and inconsistent. This is attributable to deficiencies in several areas. This article reviews a series of empirical studies, designed to address these deficiencies that investigate (a) the effects of theoretically-based Logo environments on young children’s metacognitive processing, and (b) the extent to which certain social-cognitive processes mediate those effects. Children working in the Logo environment demonstrated greater frequencies of behaviors indicative of metacognitive processing and scored significantly higher on (transfer) measures of this processing. There was less effect on planning processes (choosing a strategy for solving a problem) than on those processes that construct elaborated mental schemata for problems (deciding on the nature of the problem, selecting a representation, and cognitive monitoring). Logo children more frequently used cognitively-based resolution strategies for resolving cognitive conflict; the control
group made greater use of social negotiation. The use of cognitively-based strategies mediated treatment differences. These findings suggest that Logo fosters development of metacognitive processing, in part by engendering high-level conflict resolution. We conclude that the significant features of the Logo environment are the comprehensiveness in both cognitive and social aspects; the interaction of these two features needs further investigation.

These results have several implications for theory and research on metacognition and its facilitation by computer environments. First, we have found Sternberg’s componential theory to serve as a useful framework for describing, delineating, measuring and investigating metacognitive processing. Second, evidence supports our hypothesis that Logo programming environments, properly designed, beneficially affect students’ metacognition. A critical feature of the educational environment was the synthesis of opposites, including combining: (a) attention to both unconscious and conscious metacognition, (b) a general framework for metacognitive strategies and the embedded application of these strategies within a specific domain, and (c) individual and social-cognitive models of metacognition. This research also served to address existing deficiencies in theory and research on metacognition.

The research corpus on the use of computer environments for enhancing children’s metacognition is incomplete and inconsistent. This is attributable to deficiencies in two main areas. The first involves theoretical foundations of the research. The field has lacked an integrating theoretical model, including the (a) need for the conceptualization and definition of metacognition and metacognitive strategies, and (b) the need for theoretical connections between metacognition and features of the computer environment. The second area is methodological, including (a) measurement of metacognitive processes, (b) design, (c) description of the computer environments, and (e) examination of characteristics within these environments that mediate effects on metacognition.

This article reviews a series of studies investigating effects of theoretically-based computer environments on specific metacognitive processes. (Table 1 presents a summary of the methodology of these studies). We begin by describing how we addressed the field’s theoretical and methodological deficiencies. We then summarize our empirical findings and conclude with a discussion of implications for theory, research, and practice.
Table 1
Methodology of Studies of Metacognition and Computer Environments

<table>
<thead>
<tr>
<th>Study</th>
<th>Subjects</th>
<th>Procedure</th>
<th>Measures</th>
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<tbody>
<tr>
<td>1</td>
<td>48 early</td>
<td>Random assignment to Logo (project approach with teacher mediation) or CAI drill 14-week intervention, with two 45-minute sessions per week, working in pairs.</td>
<td>Live observations, conducted near the end of intervention stage, during work in pairs in on-computer condition and two off-computer situations (math drill and math problem solving). Experimenter-designed post-treatment measure of metacomponential functioning.</td>
</tr>
<tr>
<td>Nastasi &amp; Clements</td>
<td>elementary students (24)</td>
<td>first grade, 25 third grade, 23 female, 25 male, white, middle class, from midwestern school</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>40 elementary school students (12 fourth grade, 28 sixth grade, 16 female, 24 male); white, middle-class students; from midwestern school</td>
<td>Random assignment to problem solving group: Logo (solve posed geometrical problems) or CAI (simulations and problem-solving software). 42-session intervention (two 40-minute sessions per week), working in pairs.</td>
<td>Videotaped observations, conducted near the end of intervention stage, during work in pairs in respective computer environments. Experimenter-designed pre- and post-treatment measures of mathematician achievement and metacomponential functioning.</td>
</tr>
<tr>
<td>Nastasi &amp; Clements</td>
<td>48 third grade students (28 male); white, middle class students; from midwestern school</td>
<td>Random assignment to Logo (project approach with cartoon &quot;humans&quot; to represent specific problem-solving processes; teacher mediation of these processes in the context of the children's projects) or computer-based writing (word processing and drawing software to create illustrated compositions). 25-week intervention (2 to 3 40-45 minute sessions per week), working in pairs.</td>
<td>Videotaped observations, conducted at the beginning and end of intervention stage, during work in pairs in respective computer environments. Pre-treatment measure of academic achievement, using school-wide standardized group achievement test scores. At post-treatment, experimenter-designed interview measure of metacomponential functioning and self-report measure of perceived competence.</td>
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Theoretical Model

As a result of our research on metacognition and educational computer environments, we propose a model of metacognitive processing and development that addresses individual and environmental factors and their interaction. (See Figure 1.) The model has several assumptions:

1. An individual’s metacognition and its development are influenced by interaction with environmental influences.
2. Metacognition functions at both conscious and unconscious levels. It occurs on both global (general executive processes) and local (task-specific instantiations of these executive processes inextricably connected to domain-specific knowledge) levels.
3. Certain environmental influences serve to mediate the relationship between external stimuli and metacognitive processing within the individual.
4. Mediators can be both social (e.g., teacher or peer) and physical (e.g., educational computer environment).
5. Changes in metacognitive processing as a result of experiences in educational computer environments can be explained by interactions with the computer, the teacher, and (in the case of collaborative work) peers.

In the following sections, we describe our conceptualization of metacognition and theoretical connections between metacognition and educational computer environments.

![Diagram of our theoretical model](image)

**Figure 1.** A diagram of our theoretical model
Conceptualization of Metacognition

The term “metacognition” continues to be used in two distinct ways. The first is the conscious and purposeful reflection on various aspects of knowing and learning (Flavell, 1981; Schoenfeld, 1992). The second is the unconscious regulation of knowledge structures and learning that some information-processing theorists posit to be under the control of “executive” processes (Sternberg, 1985 #643).

Though our early work with Logo showed beneficial effects on measures of metacognition, we did not distinguish between these two types of metacognition, nor did we explicate specific executive processes. Our lack of precision made our results difficult to synthesize and explain. Therefore we developed a comprehensive theory of metacognition and metacognitive processes. For this theory, we applied Sternberg’s (1985) componential theory of cognition in describing executive-level processing. Components are elementary processes that operate upon internal representations of objects. There are three categories of components. Performance components are involved in the actual execution of a task. They perform such tasks as (a) encoding, (b) inferring, (c) mapping relationships, (d) comparing one piece of information to another, (e) combining information, and (f) responding. Knowledge-acquisition components are processes used in gaining new knowledge and in creative thought. They selectively encode, combine, and compare information to determine what is relevant, to integrate separate pieces of knowledge, and to relate newly acquired information to information acquired in the past. Knowledge-acquisition components are fundamental sources of learning, insight, and creativity. Metacomponents are executive processes that are utilized in planning, monitoring and decision-making during problem solving and task execution; that is, they are the mental operations that control a person’s cognitive functioning.

Metacomponents include deciding on the nature of the problem (determining what the task requires), choosing a strategy relevant to the solution of the problem (choosing and sequencing the necessary steps to problem solution, or planning), selecting a representation (choosing a mental model for the situation), and monitoring solution processes (keeping track of progress, recognizing an error in thinking). The existence of metacognitive processing has been documented in previous research (Clements & Nastasi, 1988; Sternberg, 1985). Furthermore, the employment of these processes is related to the application of reasoning skills to academic tasks (Clements & Nastasi, 1988; Nastasi, Clements, & Battista, 1990). In our own research, the use of metacomponential processes has been found to occur more frequently in learning environments that facilitate the development of higher-order
thinking; for example, children who work with Logo programming not only perform better on posttests assessing these processes but also exhibit the use of the processes while working with Logo (Clements & Nastasi, 1988). We postulate that conscious metacognition can be evoked by certain educational environments, especially those based on specific theories of unconscious, executive processes, and can in turn positively affect those executive processes. We explicate this stance in the following section, describing the theoretical connections between metacognition and our educational environments.

Theoretical Connections Between Metacognition and Computer Environments

We posit that certain Logo programming environments can strengthen metacomponential processing. Our two complementary rationales involve each type of metacognition, conscious reflection and unconscious executive processing (Clements, 1986b). We consider each in turn.

The first rationale is that Logo environments can encourage children’s explicit reflection on their own thinking processes. It may be possible for children to learn simple notions about the components, then use that knowledge in solving problems, and finally begin to use the knowledge automatically, without conscious direction. In other words, explicit discussions of metacomponents and Logo programming may engender metacognitive experiences (Flavell, 1981). These experiences may engender declarative knowledge that is originally interpreted by general procedures (Anderson, 1983; Minsky, 1986; Sternberg, 1985). Papert (1980) claimed that while programming children reflect on how they might do the task themselves, and therefore, on how they think. Characteristics of certain Logo environments may facilitate the occurrence of metacognitive experiences: (a) children consciously solve problems using strategies unfamiliar to them; (b) they “communicate” their organization of the task and solution processes to each other (if working in pairs), to the teacher, and to a machine; (c) they self-select problems and thus feel that they “own” Logo problems, and (d) they make errors frequently, but are given tools to correct them (Clements, 1986a; Clements, 1986b; Flavell, 1981). We further enhanced the metacognitive potential of our environment with two intervention strategies: (a) use of “homunculi”—cartoon anthropomorphisms of the metacomponential processes (Clements, 1990; Clements, 1991; Nastasi et al., 1990), and (b) settings engineered to promote positive social-cognitive interactions (Clements & Nastasi, 1985; Clements & Nastasi, 1988; Clements & Nastasi,
1992). We describe these interventions in detail in a succeeding section (“design of computer environments”).

The second rationale is that Logo environments also can serve as catalysts of unconscious componential employment. This assumes that certain features of particular Logo environments elude componential processing. For example, in both Sternberg’s theory and the psychological theory underlying Logo (Minsky, 1986; Papert, 1980), cognitive monitoring is critical to learning. Logo programming involves operations of transforming incoming information in the context of constructing, coding, and modifying causal sequences, just those actions that facilitate monitoring processes (Markman, 1981). The nature of “bugs” and their rectification are often impalpable, of course, but Logo facilitates debugging by providing graphic depiction of errors, explicit error messages, and comprehensible editing. In addition, the educational environment should provide models of debugging processes, encourage children to find and correct errors, and elicit cognitive monitoring in its most general sense through questioning. We made a similar case regarding the relationship between Logo programming and the other metacomponents (Clements, 1986b; Clements, 1990). That is, because children engage in every phase of problem solving in Logo environments, they must similarly decide on the nature of the problems and select representations and strategies to solve them.

Measurement of Metacognitive Processing

Our attempts to measure metacognitive processing have contributed to our understanding of metacognition. Our early work used some measures that fit well into Sternberg’s componential framework. For example, measures of children’s ability to realize when they do or do not understand (Markman, 1981) assessed their ability to consciously monitor their own cognitive processes. In such tasks, the interviewer presents instructions on how to perform activities, but omits crucial information for executing them. For instance, one activity involves an incomplete description of a magic trick. Children are first shown the trick, which involves “pressing” a nickel through a napkin and a saucer into a cup. Then the interviewer shows the children how to do the trick themselves. The explanation offered, however, describes the coin’s extrication from the napkin, but not its surprising appearance in the cup. The question is whether children realize they do not (could not possibly) understand.

This task was useful, with results indicating that children in the Logo programming group significantly outperformed a control group that received
Clements and Nastasi

Computer Assisted Instruction (CAI) drill-and-practice experience (Clements & Gullo, 1984). This activity, however, only measures a constrained application (comprehension monitoring) of a particular metacomponent (cognitive monitoring). Also, parallels between programming and such tasks—both Logo and the comprehension monitoring tasks involved sequences of directions—indicate a potential limitation in generalizability.

To address this limitation, we designed several interview tasks. Though still under development, most successful to this point has been a dynamic interview instrument (Clements & Nastasi, 1990). The interviewer presents problems whose successful solution is assumed to depend on intensive use of a single metacomponent. The interviewer encourages children to solve these problems without help; if the child is unsuccessful, the interviewer provides a series of five increasingly specific prompts.

For example, monitoring items induced errors by containing purposely misleading information. One problem was: “When Albert was six years old, his sister was three times as old as he. Now he is 10 years old and he figures that his sister is 30 years old. How old do you think his sister will be when Albert is 12 years old?” The prompts were: (a) “Do you have to watch out for mistakes when you do this problem?” (b) “Is there something in the problem that could trick you if you weren’t careful?” (c) “Is Albert right when he figures that when he is 10 years old his sister is 30 years old?” (d) “Will his sister always be three times as old as Albert? Is that a mistake? Should you multiply or add years?” (e) “Don’t make a mistake. When Albert was six, his sister was 18,—12 years older. What would his sister be one year later, when Albert was seven? One year later? (continue).”

We made two basic assumptions concerning the prompts. First, if students are successful on an item emphasizing a certain metacomponent (with or without the aid of prompts), then they are using that metacomponent. Second, the number of prompts needed is inversely related to the degree of retrievability of that metacomponent. Thus, fewer prompts are needed to increase the child’s score.

In our early work with the dynamic interview instrument, we attempted to observe actual use of metacomponents (Clements & Nastasi, 1990). We audiotaped children’s spontaneous verbalizations during administration of the instrument, and then coded the verbalizations using an observational scheme we developed. We were interested in whether the problem and the prompts elicited the metacomponent they were designed to elicit. For example, did children use monitoring processes more on the monitoring items than on items designed to measure other metacomponents? Examples of verbalizations for specific metacomponents are as follows: (a) Monitoring—“Wait! I think I’ve got it. The middle rung is counted two times. (b)
“Deciding on nature of the problem—”You have to figure out which goes with which of these. If the pictures were all alike you wouldn’t know what goes with it. (c) “Selecting a strategy—”Subtract my mom’s weight from the weight of my mom and the cat. (d) “Representing—”Can I do a picture?”

We also needed to measure metacognition within the Logo environment itself. We created an observation scheme and recorded frequencies of behaviors indicative of each metacomponent (Clements & Nastasi, 1988; Nastasi et al., 1990). Examples of behaviors for various metacomponents are as follows: (a) Deciding on the nature of the problem—”We’ve got to draw a square with a triangle on top”; (b) choosing a strategy—”We’ll make the turtle go up this way about 10, then RIGHT 90 and 10 down, then forward 5, and RT 90 again...”; (c) selecting a representation—”Let’s draw the figure on paper first and measure the angles”; and (d) monitoring solution processes—”Let’s think about what we’re doing. Is it gonna work?”

Although we accepted conscious use of metacognitive strategies as evidence of executive-level processing, both measurement schemes inferred such processing from other behaviors. In subsequent instrument development work, we added a think-aloud component to the dynamic interview instrument (Nastasi & Clements, 1990). Each child was asked to verbalize while thinking through the solutions for the presented items. When children failed to verbalize the solutions processes, they were asked to describe how they arrived at the solution immediately after giving a response. Think-aloud protocols were audiotaped and coded using an adaptation of the earlier observation scheme. This approach afforded the opportunity for children to make explicit their use of metacomponents and for us to observe conscious metacognition more directly.

Design of Computer Environments

Our efforts to design computer environments that facilitate metacognitive development have influenced our understanding of the mediational role of environmental features. In the past, interpretation of Logo studies has been difficult due to inadequate descriptions of the implemented computer treatments. These descriptions also give little indication of a theoretical foundation. The computer environments we have used facilitate the development of metacognition in several ways.

As stated, our later studies (Clements, 1990; Clements, 1991; Nastasi et al., 1990) emphasized explicit awareness of specific metacognitive processes and strategies. The teachers introduced specific cognitive processes via a
pedagogical device, the “homunculi”—cartoon anthropomorphisms of the metacomponential processes. For example, the Problem Decider was a person thinking about what a problem means (via a “think cloud”). The Problem Decider often asked questions such as, (a) “What am I trying to do?”, (b) “Am I doing what I really want to do?”, (c) “Have I done a similar problem before?”, (d) “How do the parts of the problem fit together?”, and (e) “What information do I have or need?” The Representer was an artist, thumb raised, looking off into the distance. She was surrounded by a piece a paper with a graph or chart, another piece of paper with writing, a drawing, and a three-dimensional model. These served as metaphors for various ways to represent a problematic situation. Teachers introduced specific representations (e.g., drawing a diagram or picture) when appropriate. The Strategy Planner was an intelligent-looking man with pencils and pens in his pocket, holding a notebook. Spaced over the remaining sessions, the teacher introduced useful strategies in the Strategy Planner’s repertoire, such as specific programming steps (described subsequently in this section), decomposing a problem, and systematically guessing and testing. The Debugger was an exterminator; a metaphor for cognitive monitoring (which is more omnipresent in problem solving than is “debugging” proper). To develop this more general cognitive monitoring, teachers frequently asked students: “What exactly are you doing? Why are you doing it? How does it help you? Does this make sense?”

Teachers introduced these homunculi as a part of the Logo-programming and problem-solving process, and used them to support four teaching methods: explication, modeling, scaffolding, and reflection (Brown, Collins, & Duguid, 1989; Cobb, Perlwitz, & Underwood, 1996; Rogoff, 1990). The goal of explication was to bring problem-solving processes to an explicit level of awareness. Teachers used the homunculi to describe processes people use to solve many types of problems. In addition, they modeled the use of the homunculi-based processes in solving actual problems. They employed scaffolding during students’ independent work with Logo; they tried to ascertain the process with which the student was having difficulty and would offer prompts and hints focusing on this particular process. When necessary, the teacher modeled the use of the process directly. Finally, they used reflection to elicit discussion about students’ use of homunculi in solving programming problems. They reviewed and encouraged use of the metacomponents as children worked on various projects emphasizing (a) basic geometric figures, (b) variables, (c) regular polygons, (d) seasonal interests, (e) contests, (f) list processing projects, and (g) collaborative work on a mural.

Teachers mediated children’s use of cognitive processes during this self-directed work, basing their interventions on the componential theoretical framework. In addition, when new information was introduced, they related it
to children’s experiences. For example, teachers introduced procedural thinking through discussions of children’s experiences with learning new routines, ideas, and words, then through the metaphor of “teaching the turtle.” Children used a support program that allowed them to define a procedure and simultaneously watch it being executed, editing whenever necessary (Clements, 1983-84; Clements & Battista, 1991).

For comparison purposes, we used placebo control groups. To avoid the Hawthorne effect, these groups received computer experience under the same conditions as the Logo group (i.e., pairs of children working with the same teachers). The control groups in our later studies used computer-based word processing and drawing tools. Thus, Logo and control treatments both included self-selection of topics and interpersonal interaction; however, the integration of Logo programming and anthropomorphic instruction in metacomponential functioning was unique to the Logo group.

Mediating Factors

In addition to designing computer environments to facilitate metacognitive development, we examined directly the environmental or ecological processes that may help account for metacognitive growth as children work within the computer environments. We have intensely investigated one—social interactions.

Although research suggests that social interaction facilitates cognitive growth, there is no consensus regarding the mechanisms that account for such change. The following have been proposed: (a) Cognitive change results from explicit conflict of problem conceptualizations (“centrations”) between individuals. (b) Alternatively, perhaps the changes in cognitive ability result from the intra-individual conflicts of conceptualizations that occur as one individual solves a problem with another even when conflict between these partners is not observed. That is, a conflict of conceptualizations may be engendered within one or both of the partners via the exchange of ideas without apparent disagreement. (c) Finally, cognitive disequilibrium may result from an individual’s interactions with the physical environment regardless of his or her interactions with a partner. In the two latter situations, the resolution of the discrepancy may occur internally (within the individual) rather than externally (between individuals). Such a notion is consistent with nonsocial components of Piagetian theory. For example, disequilibrium resulting from individual’s reflections on actions made on the physical environment are oft reported (e.g., Piaget & Inhelder, 1967).
Although conflicts of individual conceptualizations contribute to cognitive growth, collaboration may facilitate cognitive growth more than solitary endeavors. When individuals engage in a process of what we call *reciprocal sense making*, they attempt to extract meaning, generate ideas, or solve problems through a process of discourse. This type of social coordination requires that children synthesize their actions with those of other children; otherwise, the children act independently and the social “interaction collapses into parallel and uncoordinated activities” (Bearison, 1982, p. 216) and consequently is less likely to facilitate cognitive growth. This position is supported by research: Learning contexts in which students are encouraged to work together and seek concurrence are more effective in facilitating learning and cognitive growth than those in which competition or individualistic learning is encouraged (Johnson & Johnson, 1996, present a review).

Further, cooperative learning situations in which students are encouraged to disagree and challenge the thinking of their partners result in even greater gains (i.e., they scored higher on subsequent measures of achievement and perspective taking) than situations in which students are encouraged to seek concurrence and avoid disagreement (Cannella, 1993; Johnson, Johnson, Pierson, & Lyons, 1985a; Johnson, Brooker, Stutzman, Hultman, & Johnson, 1985b). Such results support the theory that interindividual conflict of conceptualizations is critical to a facilitative effect of collaborative endeavors. Indeed, Doise and Mugny (1984) report that children who engaged in cognitive conflict in the process of discussing ideas made the greatest cognitive gains. Those who discussed their ideas without apparent conflict, however, still made greater cognitive gains than those who worked alone (leaving open the possibility that cognitive growth is facilitated even when interindividual conflict is not apparent; i.e., #2 above). Although there has been little research on specific aspects of conflictive situations that account for such gains, Nastasi, Clements, and Battista (1990) demonstrated that it is the resolution of cognitive (but not social) conflict, rather the occurrence of this conflict, that is critical. Our subsequent research focused on more closely examining the nature of conflict resolution as children engaged in collaborative interactions within a Logo environment. We delineated several types of conflict resolution: (a) failure to resolve; (b) resolution through teacher intervention; (c) resolution through social means, that is, through social domination or negotiation; and (d) resolution through use of cognitive strategies, that is, discussion of ideas and/or attempts to integrate discrepant ideas (Nastasi & Clements, 1992). Furthermore, we examined the mediational role of these processes in facilitating metacomponential growth.
EMPIRICAL FINDINGS

Metacomponential Development

A fairly consistent pattern of results emerged across several studies (see Table 1). After working in the Logo environment, children exhibit a significantly higher frequency of behaviors indicative of metacomponential processing during their computer work than do children working in the control environments (Clements & Nastasi, 1988). They transfer what they have learned to noncomputer tasks (Clements, 1986a; Clements, 1990; Clements & Gullo, 1984).

Placed in the context of related research on Logo and problem solving (Clements & Merriman, 1988), the significant feature of the Logo environment that accounted for these effects was comprehensiveness in both cognitive and social aspects. Comprehensiveness in cognitive aspects is claimed in that metacognitive processes were made explicit, children engaged in all phases of the problem-solving process, and teachers used an extensive set of pedagogical approaches.

Metacomponential processes were articulated as explicitly and thoroughly as possible, as they arose in different contexts. Children were asked to verbalize their goals and solution procedures, as well as their use of metacomponential processes, before attempting a solution on computer. Contrast such attention to explicit awareness of metacomponential processes with the typical school emphasis on conveying a large body of factual knowledge, which often obfuscates higher-level thought processes.

The project approach to Logo engaged children in all aspects of problem solving, including (a) determining the nature of the problem, (b) representing different modalities, (c) selecting strategies, and (d) monitoring. In addition, both the modeling and scaffolding teaching methods allowed students to perceive the full task. Modeling provides children a schema for applying the homunculi-based processes. Scaffolding encourages successive approximation of the entire range of skills necessary for task completion.

An open question is whether it is necessary or efficient to have children spend substantial amounts of their time engaged in self-directed problem solving. Affirmation is found in the theory that, because children must build their own schemata, direct teacher instruction is insufficient—student initiation and use of higher-level processes are necessary (Simon, 1980). Supporting this, other findings from our research indicate that individual teacher-student interactions fail to account for differences on metacomponential test scores. In contrast, students’ active engagement in problem solving account for metacomponential gains.
In a similar vein, directly teaching specific strategies may not have facilitated children’s independent development and application of general higher-level thinking skills. The main function of these general processes may be to construct and activate appropriate task-specific processes. For example, general monitoring processes may instantiate themselves as part of a local system that also includes relevant domain-specific knowledge. The monitoring process in the global system gains information both about weaker but generally-applicable strategies (e.g., consciously assess progress and goals periodically) and about situations in which a domain-specific instantiation is more applicable and thus should be activated (e.g., debugging a computer program). Note that metacomponents are implicit in the local system, because the structure of that system was created by the workings of the metacomponents at the global level. However, they are “compiled” and therefore have lost flexibility; nevertheless, they leave their trace on the structure and thus operation of the local system. In summary, the Logo treatment may have taught children not so much how to apply specific cognitive skills as how to adapt metacomponential skills to the needs of specific situations. The homunculi metaphors may have served as organizational frameworks for this learning.

Results also indicate, however, that certain metacomponential processes are enhanced more than others (Clements, 1986a; Clements, 1990, note that this finding was replicated across studies using different measures of the target processes). The metacomponents of deciding on the nature of the problem, selecting a representation, and monitoring have shown significant development. This suggests schema construction; that is, a more complete construction of a mental schema for the problem, including a critic (monitor) that assesses consonance of ongoing problem-solving processes with that schema. The Logo environments have been less efficacious in developing ability to choose a strategy. It may be that regular classroom tasks and tests already provide substantial experience choosing strategies. On the other hand, such skills as deciding on the nature of the problem, selecting a representation, and cognitive monitoring are emphasized less frequently. This is consonant with other research that has reported limited impact of Logo on planning skills (Pea & Kurland, 1984).

Another possibility is that the knowledge structures created by children differed in generalizability across the metacomponents. When children were taught to choose a strategy (plan) in the Logo environment, teachers emphasized specific strategies (rather than general planning skills), such as making a “planning drawing” and writing procedures based on this drawing. The metacomponential processes may have instantiated themselves as part
of this local system. As such, they would be linked closely to the specific strategies stored there and would not be available for executive functioning in the global system. This local system would have been of limited use in the solution of other problem types, such as the tasks in the assessment instrument. In contrast, the teaching of the other metacomponential processes tended to be expressed in general terms as well as being anchored in domain-specific applications, and thus may have been more applicable to the assessment tasks. Consider the self-questioning strategies taught for deciding on the nature of the problem (e.g., “What am I trying to do?”) and monitoring (e.g., questions such as “Why are you doing what you’re doing?”, and “Does this make sense?” always preceded questions focused on specific debugging actions).

An increase in cognitive monitoring following Logo experience is one of the more consistent findings in the literature (Clements, 1986a; Clements & Gullo, 1984; Miller & Emihovich, 1986; Silvern, Lang, McCary, & Clements, 1987). We examined results for individual problems seeking patterns that might illuminate the type of knowledge being enhanced. The data suggests that the Logo environment developed general solution monitoring, rather than other aspects of problem solving such as domain-specific knowledge. Several cognitive monitoring problems on which the Logo and comparison groups did not differ required children to detect misleading information. For example, one problem presented erroneous and misleading information suggesting the doubling of the weight of a girl standing on one foot to determine her weight standing on two feet. Problems such as this probably require scientific knowledge and insight (i.e., sensitive use of knowledge-acquisition processes, Sternberg, 1985). In contrast, the three problems on which the Logo children scored substantially higher required less the possession of substantive scientific knowledge and more the evaluation of internal consistency (e.g., the “sister who was three times as old as Albert” problem). Thus, although this examination was post hoc, patterns of results suggest that the Logo environment developed general cognitive monitoring processes.

Role of Social Interactions

The Logo environment was also comprehensive in its inclusion of social aspects of learning. Children worked in pairs and teachers encouraged them to solve problems cooperatively. Observations of children’s social-cognitive processes across several studies suggest that (a) different types of educational environments engender different types of social interactions,
and (b) certain social-cognitive interactions facilitate cognitive growth, mediating the effects of the environments.

Early findings suggested that Logo facilitates peer interaction in the aid of metacomponential processing (Clements & Nastasi, 1988). Although both the Logo and CAI environments encouraged cooperative interaction, the existence of shared goals and the necessity of collaborative decision making within the Logo environment enhanced specific problem-solving skills such as conflict resolution. For example, children using CAI could simply take turns answering separate questions. In comparison, children working in Logo had to decide together what to draw as well as what strategies to use; if they did not collaborate in this way, progress was stopped. However, no connections between the observed social processes and the gains in metacomponential processing could be inferred in this study.

Building on these findings, Nastasi, Clements, and Battista (1990) demonstrated that resolution of cognitive (but not social) conflict, rather the occurrence of this conflict, is critical. First, there was no evidence of differences in amount of social conflict. Differences were found, however, in cognitive conflict, with the Logo group spending more time engaged in cognitive conflict as well as attempts to resolve such conflict. Second, successful resolution, more than the occurrence, of cognitive conflict accounted for the differential effects of Logo treatment on metacognitive processing. Thus, this study provided support for the notion that development of higher-level cognitive processes is facilitated by resolution of cognitive conflict that arises out of social interchange.

We designed a study of social-cognitive processes to identify specific resolution strategies that account for gains in cognitive functioning (Nastasi & Clements, 1992). Third grade children were randomly assigned to either a Logo or computer-based writing groups. Social-cognitive strategies that involved negotiation of perspectives emerged as most important. The resolution of cognitive conflicts was the primary mediator between the experimental treatment and gains in metacognitive processing abilities. In particular, children who resolved cognitive conflicts on a cognitive basis—that is, negotiated differences by discussing the quality of their conflicting ideas—were most likely to show gains in metacognitive processing. (Children working in the comparison group were more likely to use social negotiation to resolve these conflicts; e.g., “Well, we used your idea last time, so this time let’s use mine.”) This verifies the importance of interpersonal cognitive conflict in facilitating cognitive development. Furthermore, it serves to extend existing theory by suggesting that it is conflict resolution, more than the occurrence of conflict itself, that accounts for cognitive growth, and that certain types of resolution—those that involve attempts to synthesize viewpoints—are of particular importance.
Future research needs to determine whether this growth can be attributed to direct links between conflict resolution and higher-level cognitive activity as children solve problems or whether it results in a more indirect way from the experiences of perspective-taking and/or simultaneous monitoring of one’s own and another’s viewpoint during problem solving. In addition, we observed social-cognitive interactions occurring spontaneously as children worked within a specific Logo environment. Future research efforts might focus on interventions designed to facilitate the use of such processes, thus experimentally evaluating their efficacy. They should also investigate the contribution of other aspects of the pedagogical environment, such as the cognitive aspects of the comprehensive environment employed in this study, as well as the interaction of the social and cognitive aspects.

Role of Logo

The Logo language itself undoubtedly constitutes neither a necessary nor sufficient condition for cognitive growth. Nevertheless, we argue that Logo can play an important catalytic role. Logo is particularly suited to implicit evocation of metacomponential processes and to the promotion of metaphorical thinking in aid of those processes. That is, the isomorphism between the information-processing framework in which Sternberg’s componential theory is embedded and Logo’s computer science framework allows the act of procedural programming to serve as a metaphor for componential functioning. Children’s solutions in Logo have been externalized; they are now the turtle’s solutions. Logo procedures can be used as metaphors for mental schemata representing solutions to problems; thus, the latter become “more obtrusive and more accessible to reflection” (Papert, 1980, p. 145) and more likely to encourage thinking about thinking. This process-oriented procedure itself can serve as a metaphor for componential functioning; for example, debugging Logo procedures as a metaphor for cognitive monitoring. Thus, Logo can serve as a tool that facilitates the role of the teacher as a mediator of metacognitive experiences.

It addition, Logo environments such as those used in the studies reviewed here facilitate peer interactions focused on learning and problem solving more than traditional classroom tasks or CAI. They encourage self-directed problem solving (i.e., children solve problems that they themselves have posed, with support but not direction by the teacher) and mutual “ownership” of the problem. Finally, they engender conflict and negotiation and resolution of that conflict (Clements & Nastasi, 1985; Clements & Nastasi, 1988; Nastasi et al., 1990). In particular, they engender a high-level type of conflict resolution—cognitively-based resolution of cognitive conflicts.
THEORETICAL IMPLICATIONS

Our results have several implications for theory and research on metacognition and its facilitation by computer environments.

Conceptualization and Measurement of Metacognitive Processing

In this line of inquiry we investigated the use of two experimental approaches, an observational and a dynamic assessment instrument, for measuring students’ higher-order intellectual processing. Results supported the use of Sternberg’s componential theory for defining young students’ higher-order processing and the use of a Vygotskian perspective for developing nontraditional measures. There was also evidence of acceptable levels of reliability and construct and criterion-related validity. Analyses confirmed that although the dynamic assessment instrument may measure content knowledge to some degree, it does measure metacomponential processing.

Consonant with previous research, the instruments provide mixed support for delineation of the metacomponents (Clements & Nastasi, 1988; Sternberg, 1985). The observational data do suggest separable phases of componential processing, including those that involve (a) defining the problem, planning the solution, and monitoring ongoing problem solving (all metacomponents); (b) responding to external feedback about problem solution (another metacomponent); and (c) actual solution of the task (i.e., performance components). Interrelationships among the metacomponents (i.e., within phase “a”) may be responsible for the frequent observation of a “general” factor of intelligence (Sternberg, 1985). On the basis of these data, however, we can conclude only that the metacomponents are related; that is, frequency of use of one metacomponent is correlated with frequency of use of other metacomponents. It remains open as to whether the metacomponents actually operate as separate processes in intellectual activity (as opposed to a single global factor), or whether separate metacomponents exist, but are fewer in number or different than those proposed by Sternberg. The lack of differentiation of the metacomponents might also suggest the viability of parallel distributed processing (McClelland, Rumelhart, & the PDP Research Group, 1986), or connectionist, models of metacognition.

Similarly, individual metacomponential scores from the dynamic assessment instrument were interrelated. Nevertheless, close examination of students’ responses to the problems and prompts supported delineation of the metacomponents. Their responses reflected the use of those metacomponents the tasks were designed to elicit. That is, students were responding as predicted to the dynamic instrument’s mediation.
The results of these studies suggest the criticality of considering context in which assessment is conducted. Valid assessment requires accounting for how the environment influences the intellectual behaviors that are observed. At least two alternatives are possible. First, one might create an environment through the use of structured tasks that are likely to elicit the target processes. The dynamic assessment model seems to have accomplished this through the use of specifically-designed tasks and a mediated assessment approach. With prompts, students evinced a greater amount of metacomponential processing and more successful performance. Such observations might lead to conclusions of greater competency and learning potential.

Furthermore, use of think-aloud procedures may provide a method for assessing conscious use of metacomponential processes. For example, in response to the problem designed to measure Selecting/Combining, “John wanted to know how much his cat weighed. But the cat wouldn’t stay on the scale unless he was holding it. How could he figure out the cat’s weight?” One child responded with an explanation of the steps he would use, consciously relating it to his previous experiences: “Umm...First he could weigh himself with the cat. Then he’s got his weight in there. So he weighs himself, and sees how much it is. Then he could minus his weight from the first one and that’s the cat’s weight!”

A second alternative is to observe the student within a natural setting in which the uses of such processes is encouraged. We observed students in two educational environments designed to encourage the use of higher-order processes to different degrees. Results confirmed that students more frequently exhibited metacomponential processing in one of these environments. In this high-support environment, students worked cooperatively and shared responsibility for completing self-selected projects. This resulted in student-student mediation characterized by interpersonal cognitive conflict and negotiation of problem definition and solution strategies (Clements & Nastasi, 1988; Nastasi & Clements, 1992). Note that had we observed students working only in the low-support environment, we might have made quite different conclusions about their ability and potential. Thus, care must be taken not to conclude lack of ability or potential when such opportunities have not been provided within the assessment environment. In conducting assessments within natural settings such as the classroom, it is important to determine the extent to which that setting supports the use of the target behaviors. A combination of these two approaches is consistent with current best practices in assessment, as it serves to enhance reliability through multiple methods and to insure ecological validity through observation in actual educational contexts.

Considerations of context also have implications for making predictions from assessment results. For example, our results intimate that the use
of specific metacomponents is context-bound. Different metacomponent subtests of the dynamic assessment instrument predicted different aspects of achievement. Monitoring predicted computation, whereas selecting and combining and representation predicted mathematical reasoning. Thus, attempts to predict academic achievement should take into account the higher-order processes used in performing specific academic tasks.

In conclusion, the two experimental approaches may ameliorate some of the problems associated with the use of traditional intelligence tests. They are theoretically grounded, being based on a synthesis of the theories of Sternberg and Vygotsky. Compared to traditional tests, the Vygotskian approach of mediated assessment may more effectively assess intellectual potential and reduce variability due to interindividual differences in experience. The importance of context is addressed in the ecologically valid observational approach and a dynamic assessment approach that encourages and supports the use of the processes to be measured. Finally, the approaches emphasize the assessment of process, compared to traditional tests’ tendency to measure acquired knowledge and performance processing at the expense of metacomponential processing (Sternberg, 1984). For example, children who were unable to correctly solve problems with mathematics content because of poor computation skills, with the aid of prompts exhibited excellent understanding of the conceptual nature of the problem and the processes necessary for reaching a correct solution. On a traditional school test, children would receive no credit unless the correct solution was reached.

Several research issues remain to be addressed. First, there is a need to investigate developmental differences in higher-order processing and in the importance of this processing for learning. Second, our method for observing behaviors indicative of higher-order processing within a dynamic assessment procedure needs extension and validation. This method may combine the control of the standardized approach with direct observation of processes within a problem-solving context designed to elicit the use of target processes. Third, the generalizability of metacomponential processes needs to be investigated; for example, through observations within a wider variety of classroom environments and across different academic tasks. Fourth, procedures should be developed to assess the extent to which the environment encourages and supports this type of processing. Next we describe our work in developing and evaluating such educational environments.
Social-Cognitive Processes and Metacognition

Our studies have two implications for social-cognitive research and theory. First, they provide further evidence of the criticality of conflict resolution. Previous research has suggested that engagement in conflict will not necessarily lead to cognitive advances; indeed, merely disagreeing with others has been shown to impede advances in moral reasoning (Damon & Killen, 1982). Students have to go beyond mere disagreement to benefit from the conflict of ideas (Bearison, Magzamen, & Filardo, 1986; Damon & Killen, 1982). Our research strongly supports such findings; it is conflict resolution, not the occurrence of conflict itself, that accounts for growth in higher-order thinking. Second, our findings extend existing social-cognitive research by determining that certain resolution strategies—those that involve attempts to synthesize viewpoints—are of particular importance. We did not examine the extent to which the final solution reflected a true synthesis (combination of the ideas into a third, well-integrated coherent and qualitatively different idea). The partners needed only to achieve some compromise position that was reached by considering the quality of the divergent views. Future research could address such distinctions.

Research also needs to determine whether cognitive growth can be attributed to direct links between conflict resolution and higher-order cognitive activity as students solve problems, or whether it results in a more indirect way from the experience of taking another’s perspective. In addition, we observed social interactions occurring spontaneously as students worked together. Researchers might directly intervene to encourage the use of processes such as cognitively-based conflict resolution, thus experimentally evaluating their efficacy.

Finally, findings such as those reviewed here do not imply that explicit interindividual conflict and its resolution are solely responsible for gains in higher-order thinking (these social processes typically account for only 10 to 15% of the variance in higher-order thinking scores). Perhaps the changes in cognitive ability result from the intraindividual conflicts of conceptualizations that occur even when conflict between partners is not observed. That is, a conflict of conceptualizations may be engendered within one or both of the partners via the exchange of ideas, even without observable disagreement (i.e., reciprocal sense-making). Finally, cognitive disequilibrium may result from an individual’s interactions with the physical environment regardless of his or her interactions with a partner. In these situations, the resolution of the discrepancy may occur internally (within the individual) rather than externally (between individuals). It may be that some combination
of the three postulated mechanisms of cognitive change—(a) interindividual conflict, (b) collaboration without observed conflict, and (c) intraindividual conflict (possibly with a minimal level of one or more of these)—are necessary for optimal growth.

Of course, previously described cognitive aspects of educational environments also may be important (Clements, 1990). For example, in these environments, higher-order thinking processes are made explicit, students engage in all phases of the problem-solving process, and teachers use a comprehensive set of pedagogical approaches. Higher-ordering thinking processes are articulated as explicitly and thoroughly as possible, as they arise in different contexts. Teachers ask students to verbalize their goals and solution procedures, as well as their use of these thinking processes, before attempting a solution on computer. The project approach to Logo engages students in all aspects of problem solving, including determining the nature of the problem, representing the problem in different modalities, selecting strategies, and monitoring. In addition, both modeling and scaffolding allow students to perceive the full task. Modeling provides students a schema for applying the homunculi-based processes. Scaffolding encourages successive approximation of the entire range of skills necessary for task completion. Future studies should investigate the contribution of these cognitive aspects of the pedagogical environment, as well as the interaction of the social and cognitive aspects.

**Delineating Cognitive Conflict’s Effects: Connections to Information Processing Theory**

The theoretical foundation for the role of cognitive conflict in the development of higher-order thinking originates in the Piagetian research paradigm. We posit that this theory must be elaborated to build connections to the information-processing foundation of metacomponential processing, and further, to Vygotskian conceptions of the internalization of interpersonal interactions. We propose that when one works with a partner, one builds and elaborates a mental model of the partner’s thinking (in this case, an active conflict-creating person, cf. Minsky, 1986). Interactions with the partner are based on this mental model—in brief, one compares what one knows and wishes to communicate about a specific problem situation to what (the model of) the partner knows and believes about that situation; the differences are used to construct a series of speech acts designed to bring the partner’s thinking about the problematic situation (as represented in the model)
into closer correspondence with one’s own knowledge and beliefs. Partners respond to each other in this way.

Conflict may occur either when the partner’s expressed ideas are not consonant with those in the model and thus the model must be modified, or when the model (especially after modification) is perceived as viable but inconsistent with one’s own knowledge and beliefs. These conflicts may or may not enter into the dialog and may or may not be resolved. In either case, however, conflict and attempts at resolving such conflict can serve the function of forcing to a level of explicit awareness aspects of cognitive processes of which people are usually not conscious. Stated simply, people are not as likely to be aware of the mechanisms of their cognition until something goes wrong (Flavell, 1981; Minsky, 1986). Conflict on the external, interpsychological plane may be most likely to have such an effect. Further, conflict engenders metacomponential processing even if such explicit awareness does not occur. Conflict-based perturbations force processing out of any domain-specific, or local system (which can include compiled, and therefore efficient but rigid, instantiations of the metacomponential processes), evoking the monitoring metacomponent of the global system. This global monitoring metacomponent not only (a) keeps track of what has been done, (b) what is currently being done, and (c) what needs to be done, but (d) also controls intercommunication and interactivation among the components (Sternberg, 1985m). Through this process, each of the metacomponents undergoes development as they adjust their functioning on the basis of feedback they receive from other components; that is, they “learn from their own mistakes,” accruing information about where, how, why, and especially when the various components might be applied. Whether conscious or unconscious, such conflict-driven learning leads to both more effective metacomponential processing and to modification of one’s model of the partner and one’s representation of the specific problem at hand.

Traces of each such interaction are recorded (unconsciously and automatically). The monitoring metacomponent reviews these traces; repeated patterns of interactions are abstracted to form a scheme—a template that serves to recognize future experiences as similar and to anticipate subsequent interactional patterns and the results of such interactions. Because the model of the partner, the patterns of interaction with the partner, and scheme abstracted from this pattern are all constructed by the individual, there is the potential for that individual to reinstantiate the scheme (e.g., represent or replay the dialogues—inner speech in Vygotskian terms) even in the absence of the original partner—with new partners and, potentially,
alone. At this time, we can say the process has been internalized as a cognitive function or tool.

Consider the following vignette. Students are creating a hexagon using Logo. They have already made two sides of the figure; Student 1 suggests turning the turtle 180° to move around the opposite way, but Student 2 disagrees (adapted from Clements & Nastasi, 1992).

Student 1: Right 180.

Student 2: No! [cognitive conflict] Because 180 would go (gesturing)...we want it to go, shh-shh-shh-shh-shh (gesturing to indicate that the hexagon can be completed by continuing the same way), we only have to repeat that 5 times. [attempt at cognitively-based resolution, with an idea-based rationale accompanying the objection]

Student 1: Oh, OK. [cognitively-based resolution successful] But 4 times. [cognitive conflict]

Student 2: No, 1, 2, 3, 4, 5. ‘Cause that one’s already there. [attempt at cognitively-based resolution]

Student 1: 1, 2,... 1, 2, 3, 4, 5, 6.

Student 2: 4.

Student 1: Yes. [cognitively-based resolution successful]

For these two students, the decision-making process involved logical consideration of the relative merits of alternative solutions for goal accomplishment. A consistent interactional pattern for this dyad was for one student to disagree, then the other to defend his own initial idea. As the interaction progresses, the pattern changes, as can be seen in the following dialogue. Student 1 presents his rationale for a proposed solution even before his partner objects, as if in anticipation of a counterproposal.

Student 1: We have to put the left 125, because the turtle will be there, and it will slip around and go shh, shh, shh (gesturing). [an attempt at cognitively-based resolution] Try it over. Now right 125.

Student 2: Left. [cognitive conflict]

Student 1: Left 125. Yes. [cognitively-based resolution] Back down. Left 125. Repeat 6, to make sure it will do the whole thing. [idea-based rationale for the proposed solution, even before an objection
can be raised]. Oh, you forgot the bracket. Bracket, forward, space left, left, 60, bracket, end. Try it. Please let it work. Ugh.

Student 2: It’s no good.

Student 1: Look how close we got it though. It’s off, we didn’t have it at a steep enough angle, we have to make it 130. Oh, and it’s so close. 130. Too much.

Student 2: Put it right 10.

Student 1: 120, like I said. Left 120, try it. We did it! Yes! Teacher, we got it!

Despite the cognitively conflictual nature of the interchange (they disagree about ideas related to problem solving), the partners are still collaborating. Such interactions were typically very productive and reflected a friendly affective tone. Students were disagreeing about ideas, not making ad hominem attacks against their partners. The focus was on goal attainment; who contributed what seemed to be unimportant.

We hypothesize that Student 1’s monitoring metacomponent, motivated by concerns both about efficiency and affective concerns such as minimizing criticism, attenuated the interpersonal interaction pattern by internally (a) reinstating (running) the mental model of the other person with the input constituted by one’s current ideas; (b) anticipating possible objections or criticisms from the partner, and (c) answering those objections or criticisms externally (i.e., explicitly justifying his thinking).

In sum, the cognitive residue of repeated interpsychological interactions is each individual’s appropriation of his or her own interpretation of the social interaction (c.f. Rogoff, 1990). As the scheme is applied to a number of increasingly variant situations, it becomes more disassociated from its original roots and increasingly useful as a tool for individual problem solving. This ties closely to the Vygotskian notion that mental processes are internalized social relations that become functional for the individual. As a result of the social interaction, then, internal implicit thoughts are made explicit and communicative, and external dialog is appropriated and internalized (Vygotsky, 1934/1986). In this way, children enhance both conscious and unconscious metacognitive processes. We have evidence that metacomponential growth occurs at least at an unconscious level and that certain social processes may be facilitating this growth. However, we need to examine more closely the evolution of metacomponential thinking as students interact within certain Logo environments. The more explicit delineation
of the links between social interchange and metacognitive development in real-life educational contexts is expected to contribute both to theory development and educational practice. Furthermore, encouraging children to reflect on their problem solving may facilitate both the use and assessment of conscious processes (e.g., asking children to think aloud as they problem solve or to reflect on videotaped interchanges during collaborative problem solving). Through action research in a specific educational context (classroom) over an extended period of time (e.g., an entire school year), we may be able enhance theory-research and practice links more efficiently. In such research, other factors shown to correspond to high-level cognition, such as time allocated to tasks and resisting the pull towards reducing task complexity, must also be considered (Henningsen & Stein, 1997).

Research Approaches

To a great extent, an action research model characterizes the evolution of our research program. Action research is an interactive model of theory, research, and action/practice that guides applied social science (Schensul, 1985). Theory guides the generation of applied research questions and data collection, for example, regarding the manifestation of metacognitive or metacomponential processes in young children. These data provide the basis for reformulating theory, for example, as applied to young children’s learning; and developing (educational) interventions, for example, to facilitate the development of metacomponential thinking. Intervention outcomes, documented through data collection, then influence development of theory and subsequent interventions, and so on. The process is recursive and depicts the evolution of an applied research program such as ours. We believe that more conscious, purposeful use of action research methods within specific studies would be desirable; for example, by recursively testing theory in practice and then evaluating practice to further enhance theory throughout a given study.

Conclusions

In sum, we have found Sternberg’s componential theory to serve as a useful framework for describing, delineating, measuring, and investigating metacognitive processing. Further, evidence supports our hypothesis that Logo programming environments, properly designed, beneficially affect students’ metacognition, consistent with other research (Fletcher-Flinn & Suddendorf, 1996; Lehrer & Littlefield, 1993; Yelland,
1994). A critical feature of our educational environments was the synthesis of opposites, including combining: (a) attention to both unconscious and conscious metacognition, (b) a general framework for metacognitive strategies and the embedded application of these strategies within a specific domain, and (c) individual and social-cognitive models of metacognition.

**Model of Metacognition**

Returning to our model of metacognition (see Figure 1), we summarize our explanation of how educational computing environments may facilitate metacognitive processing. We examined the role of both social and physical (computer) mediators of metacognitive processing and growth within assessment and intervention contexts. Social mediators included both adults—the teacher in the Logo classroom and the assessor in the metacomponential interview, and peers-partners in collaborative work at the computer. The primary physical mediator we examined was the computer, particularly through the use of Logo programming. In every case, language (human and computer programming) served to mediate the learner’s relationship with external stimuli (e.g., problems to be solved, information to be processed). We propose that these mediators operate in a manner consistent with Vygotsky’s notions of mediation. That is, the person and/or computer guides or constrains the individual’s interpretation and manipulation of information. These mediators serve to mirror or engender metacognitive processes. The computer engenders conscious use of global metacognitive processes. The teacher, through instructional strategies (scaffolding, modeling, explanation, and reflection) and the aid of homunculi, also engenders conscious use of global processes. The assessor’s use of the dynamic assessment process in the metacomponential interview stimulated the use of unconscious global and local processes. Finally, through collaborative problem solving, peers stimulated both conscious and unconscious use of global and local processes. The mediation process served to both facilitate the use of metacognition within the learning context (as evidenced in our observations) and fostered the development of metacognitive processes (as evidenced in outcome measures).
Educational environments hold promise for facilitating metacognitive processing and growth to the extent that they embody certain mediating factors. The complex teaching-learning process involves the learner’s interactions with both social and physical aspects of the learning environment—social interactions between teacher and student and among students, problem content and context, instructional strategies, and tools such as computers. The educator plays a key role in the design and coordination of the social and physical aspects of the learning environment.

Our research suggests that the computer environment plays a significant role in engendering learning. Logo served as a tool that facilitates the role of the teacher as a mediator of metacognitive experiences. In addition, Logo environments encouraged collaborative problem solving and engendered conflict and negotiation and resolution of that conflict. Perhaps most important, even compared to other problem-solving, open-ended computer environments, Logo environments engendered a high-level type of conflict resolution involving coordination of divergent perspectives. Thus, evidence suggests that the use of Logo is not an arbitrary decision. Nevertheless, future practice and research might ascertain whether other tools, including other programming languages, scripting environments, construction tools, and simulations, can serve similar functions. Teachers and researchers might evaluate the relative capacity for these programming environments to (a) encourage self-directed problem-solving, (b) support mutual “ownership” of problems and solutions, (c) elicit conflict and negotiation and high-level resolution of that conflict, (d) engender conscious metacognitive experiences, and (e) serve as catalysts of unconscious componential employment. Evaluation of the contribution of each of these factors to the development of metacognitive thinking, as well as domain-specific (e.g., mathematics) knowledge, also is warranted.

The use of any program to develop metacognitive capabilities, and especially to provide conscious metacognitive experiences, is not without critics. Some maintain that efforts to develop higher-level thinking should be integrated throughout the curriculum (see Ennis, 1989; Snow, 1989, as well other articles in the same issue). Indeed, transfer effects in this study may have been attenuated due to the lack of infusion into children’s usual school lessons. Although such integration is advisable, infusion often leads to diffusion, severely limiting the focus and impact of the program (Clements,
In addition, it is difficult for teachers to maintain high-level teaching methods such as explication, modeling, scaffolding, and reflection, especially in the context of teaching traditional subject matter (cf. Pogrow, 1988). Therefore, a program such as used here, that focuses specifically on higher-level thinking, but simultaneously develops ideas in the domains of computer science and mathematics (Clements & Battista, 1989), may make a substantive contribution to children’s cognitive development.

However, we need research that will address each of these issues. For example, research with Logo and the other environments named might specifically compare various approaches, including integrated, infused approaches; separate programs specifically designed to develop metacognitive abilities such as those reported here; and programs in which metacognitive skills are never specifically “taught,” but higher-level concepts in specific subject-matter domains are emphasized. Such studies, although difficult, would provide answers to ongoing theoretical debates that show no sign of resolution due to the lack of empirical evidence.

In addition, such environments appear to support the development of motivated learners who seek to validate their ideas not only through their own reasoning, but also through meaningful communication with others. Development of this type of student is consonant with reform positions of such organizations as the National Council of Teachers of Mathematics (NCTM), which supports the cultivation of students who believe “that they have the power to do mathematics and that they have control over their own success or failure,” and “explain, conjecture, and defend” their ideas (1989, pp. 29, 78).

Just as important from the NCTM’s perspective, is the growth in metacognitive abilities. From this perspective, students should approach mathematics as problem solving. Because Logo initially was created as a tool for learning mathematics, children developed their metacognitive abilities while posing and solving mathematics problems. Our approach, then, combines the benefits of teaching metacognition in a domain-specific context (Schoenfeld, 1992) and as explicit habits of thinking (Perkins & Salomon, 1989).

We have designed a new computer environment, *Turtle Math™* (Clements & Meredith, 1994), on the basis of research conducted by ourselves and others (for details, see also Clements & Sarama, 1995) and on recent recommendations for reform. A version of this environment is also integrated into the geometry units of the Investigations in Number, Data, and Space curriculum funded by the National Science Foundation (e.g., Clements, Battista, Akers, Rubin, & Woolley, 1995a; Clements et al., 1995b; Goodrow, Clements, Battista, Sarama, & Akers, 1997). Although we have
not measured metacognitive effects separately, evaluations of Turtle Math in a variety of classroom settings have been consistently positive, especially regarding the learning of mathematics (Clements, 1995; Clements, 1996; Clements, 1996; Clements, Battista, & Sarama, in press-a; Clements, Battista, Sarama, Swaminathan, & McMillen, 1997; Clements & Sarama, 1997; Clements, Sarama, & Battista, in press-b). These findings may indicate that our results have implications for “real-world” teachers and classrooms. Future work should assess the generalizability of the results to different computer environments.

Furthermore, efforts to investigate the role of teacher and peers in facilitating metacognitive growth within varied computer environments are necessary to determine the relative contributions of the social aspects of the environment. In addition, the role of the teacher and the computer environment in the development of motivated, empowered students (e.g., as endorsed by NCTM) warrants further study. Such investigation requires the active participation of teachers and students in the research process. Participatory action research (PAR) models provide a mechanism for both the participation and empowerment of key stakeholders e.g., teachers and students, see Nastasi, Varjas, Sarkar, & Jayasena, 1998). PAR can facilitate the effective integration of research and theory into practice through collaboration of teachers, students, and researchers in the creation and testing of computer environments that embody aforementioned critical factors to different degrees. Finally, use of PAR can facilitate the development and testing of assessment models that are ecologically valid and closely linked to interventions (Nastasi & Berg, in press). That is, teachers and researchers together can investigate the validity of mediated assessment tools that are integrated into the curriculum (e.g., using observational and dynamic tools in the context of instruction), thus fostering ongoing evaluation of instruction. Such models may play an important role in filling the gaps we have identified in the research.

References


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