Instructional Science (2007) 35:207–256
DOI 10.1007/s11251-006-9005-2

Reframing research on learning with technology: in search of the meaning of cognitive tools

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Received: 13 October 2004; accepted: 29 June 2006

Abstract. Previous research and development with cognitive tools has been limited by an inadequate conceptualization of the complexity underlying their nature and affordances for supporting learning and performance. This paper provides a new perspective on cognitive tools through the lens of the theories of distributed cognition and expertise. The learner, tool, and activity form a joint learning system, and the expertise in the world should be reflected not only in the tool but also in the learning activity within which learners make use of the tool. This enhanced perspective is used to clarify the nature of cognitive tools and distinguish them from other types of computer tools used in learning contexts. We have classified cognitive tools considering how expertise is classified: domain-independent (general) cognitive tools, domain-generic cognitive tools, and domain-specific cognitive tools. The implications are presented in reference to research, development, and practice of cognitive tools. The capabilities of cognitive tools should be differentiated from those of the human, but regarded as part of the system of expertise. Cognitive tools should be accompanied by appropriate learning activities, and relevant learner performance should then be assessed in the context of tool use.

Keywords: cognitive tools, distributed cognition, expertise, human–computer interaction, learning activity, learning technology, theoretical framework

Introduction

In the past, proponents of educational technology have argued that there simply were not enough computers, software, or support in classroom to have significant impact on educational outcomes. Over the last decade, however, the ratio of students to computers has steadily improved, increasingly powerful software packages have become widely available, and assistance for teachers and faculty has been increased through the introduction of technology coordinators in

K-12 schools and additional technology support personnel on college and university campuses (Becker, 2000; Pittinsky, 2003). Despite enormous increases in technological infrastructure and support, it still remains difficult to find evidence of significant impact of computers on teaching and learning at any level of education (Cuban, 2001).

Many of the problems with how people view, develop, use, and study computers in education stem from thinking about computers within the framework of long-established mainstream educational practices. As described in Jonassen and Reeves (1996), much of the disappointing results of the application of computers in education can be attributed to a misguided emphasis on using technology as something that students should learn "from" in a fashion similar to how they might learn "from" classroom teachers, textbooks, or television. Although the conceptualization of using computers as tutor, tool, and tutee was proposed a quarter century ago (Taylor, 1980), researchers and practitioners have more recently attempted to employ computers as "cognitive tools" for learners to learn "with" while they are solving problems or completing tasks (Lajoie and Derry, 1993b; Lajoie, 2000). Unfortunately, immature use of computers as cognitive tools has also led to disappointing results. Instead of using computers as tools to learn "with," teachers focused on helping their students to master the tools themselves. This approach has been justly criticized as schools trying to teach "hammer" instead of "carpentry" (Oppenheimer, 1997).

Cognitive tools to date: issues and a need

The scholarship of cognitive tools is founded on constructivist beliefs about how learning occurs and how learning environments should be designed accordingly. Although complex and rife with controversy (Phillips, 2000), constructivism in education can be boiled down to the concept that learners actively construct their own knowledge rather than passively receive it (von Glasersfeld, 1995). Constructivist learning requires constructing our meanings through reflection and continuously reconsidering our existing interpretations of the world (Salomon and Almog, 1998). Although cognitive constructivists such as von Glasersfeld (1995) emphasizes individual construction of meaning, social constructivists "reject the notion that the locus of knowledge is in the individual" (Prawat, 1996, p. 217), viewing knowledge creation as more of a shared experience than an individual one.

The results of the cognitive activities of learners should be the consequences of constructing knowledge ‘‘with’’ computer tools rather than learning ‘‘from’’ computer tutorials in a manner previously structured by someone else. The focus on the use of computer tools for cognitive activities for learners to think ‘‘with’’ is derived from the theory of distributed cognition (Salomon, 1993c). Distributed cognition implies that learners are enabled to think deeply and create certain types of artifacts that represent their thinking by working with cognitive tools.

In general, physical tools are utilized to enhance the performances of human activities (e.g., digging a hole in the ground) or to do tasks otherwise impossible (e.g., examining cell structures of fruit flies). Tools for cognitive activities are comparable to the physical tools that are invented for everyday human activities in that they change and enhance our way of doing mental activities, create new ones, and are steadily improved as they are adopted and used by more and more people. A good example of the development, effects, and refinement of cognitive tools is the way that mathematical symbols have evolved throughout history.

The conceptualization of computers as cognitive tools has been refined and the development of actual cognitive tools has progressed greatly in recent years (Nickerson, 1993). Unfortunately, researchers have used different names to signify the application of computers to advanced mental activities, such as cognitive technologies, technologies of the mind, cognitive tools, and mindtools (Jonassen and Reeves, 1996). Salomon et al. (1991) describe computers as ‘‘partners in cognition’’ that extend human cognitive capabilities. Given the abstractness of the term, it is hardly surprising that researchers and theorists proposing these new ideas about cognitive tools have expressed diverse views (Lajoie, 1993; Salomon, 1993a; Jonassen, 1996).

These different labels share similar connotations with both physical tools (e.g., hammer) and intangible mental tools (e.g., symbols) in that they help by enhancing or extending human capabilities (e.g., Falbel, 1991; Salomon et al. 1991; Lajoie, 1993; Salomon, 1993b; Jonassen and Reeves, 1996). At the simplest level, cognitive tools can be defined as aides for cognitive tasks such as complex calculations (Lajoie, 1993). With more elaboration, Jonassen and Reeves (1996) characterized cognitive tools as ‘‘technologies that enhance the cognitive powers of human beings during thinking, problem solving, and learning’’ (p. 693). By enhancement, they meant that people can have deeper, more reflective thoughts by distributing mundane tasks to the tools (e.g., calculations), or are able to perform cognitive tasks impossible without such tools (e.g., modeling complex interactions) (Jonassen and Reeves, 1996).

Salomon (1993a) added more conditions to explain cognitive tools by suggesting that they are open-ended instruments that students operate and manipulate to help themselves engage in constructive thinking, allowing them to think beyond their cognitive limitations. The "open-endedness" is important in Salomon's definition because it signifies that students are the ones who actively make decisions about their mental processes and the need for cognitive support.

The movement to use computers as cognitive tools or partners in education over the last decade has not progressed to the degree that has long been desired by advocates such as Lajoie (1993), Jonassen (1996), Papert (1993), Salomon (1993c), and others. Perhaps cognitive tools researchers should be more mindful and reflective in defining what makes a computer program a cognitive tool. One prominent issue is whether the nature or the use of a tool makes it a cognitive tool. Lajoie and Derry (1993a) introduced cognitive tool initiatives that basically have three different natures: modelers of learners' thinking, non-modelers, and initiatives that combine the two. Others have discussed computer tools as specially designed cognitive "partners" (Salomon, 1993b). By contrast, Jonassen and Reeves (1996) focused their discussion on the use of everyday computer programs such as spreadsheets and databases as cognitive tools that learners' employ for knowledge construction.

There are other issues that contribute to sometimes confusing conversations about cognitive tools. The notion of cognitive tools has been explored by many scholars, but still remains somewhat abstract, thus limiting progress in research, development, and application. Not only does the very concept of cognitive tools remain ambiguous, but problems muddle its associated ideas for research and practice:

1. There is a lack of understanding about the design and values of cognitive tools;
2. Adoptions of cognitive tools in classrooms are too brief and/or inappropriate; and
3. Disintegrated research approaches do not provide sufficient feedback to advance the fundamental ideas.

The lack of understanding of design and values

Even the simplest invention, such as plastic cups, has benefits and losses, e.g., consumer convenience and environmental pollution.

Cognitive tools also have their trade-offs of which we must be mindful (Pea, 1993). Many people have come to rely on email communications, and yet at the same time, some miss the intimacy of hand-written letters. The activities inherent in writing a traditional letter, such as choosing good stationary and a fine pen, presenting content within the guidelines of certain formats, writing addresses, and attaching stamps, are either transformed or completely lost in an electronic format. With respect to using cognitive tools in education, we should think about whether we are providing cognitive tools that transform learners' cognitive activities toward higher-level thinking, or providing them with future disabilities by requiring the use of cognitive tools in the formal learning environment, but expecting learners to do without them outside of schools. For example, according to a recent report (Levin and Arafeh, 2002), some middle and high school students have become so reliant on the Internet as a source for educational content and instruction that they have come to view traditional media (e.g., textbooks) and even their teachers as irrelevant.

Falbel (1991) addresses another design issue by seeing a tool by itself as both value-neutral and value-laden. Tools embody certain values imposed by their design, but they are value-neutral until used in certain ways by particular learners (Falbel, 1991). The choices that learners make to use cognitive tools can be more open or limited depending on the nature of the tools and the design of the learning environment in which they are to be employed. Educators should be aware of both the value that cognitive tools bring to the fore in any educational context as well as the possibilities they open up for the learners. Cognitive tools can be developed with elaborate features intended for higher-level learning and thinking, but problems arise when the value of them are not seen by the learners or are not reflected in learning activities. Although some studies report advances in using cognitive tools in formal instructional contexts, most such studies report that learners were often unable to use the various features of tools to go beyond modest expectations (e.g., Brown et al., 1993; Edelson et al., 1999; Spitulnik et al., 1999).

The brief and/or inappropriate adoptions

It is a dubious assumption that learners will automatically take appropriate and measured advantage of the affordances of computer tools when involved in cognitive activities with them (Perkins, 1993; Salomon, 1993a). For cognitive tools to actually become an extension of human cognition, learners must strive for mindful engagement in activities. Mindful engagement requires learners to be fully involved in examining novel, multiple perspectives and categories when problem-solving (Langer and Moldoveanu, 2000). Unlike films that automatically generate movement and sound to gain passive attention from people, cognitive tools require deliberate attention and effort from learners to make use of the affordances of the tools. Learning activities requiring cognitive tools are not as effortless as watching a multimedia presentation, which perhaps could fall into Mayer's (2001) narrow definition of multimedia learning as "learning from words and pictures," but as vigorous as creating one. Learners should be mindful and reflective in working with cognitive tools through deep thought, comparison and contrast, and decision-making beyond the experience of predetermined arrangements of words and pictures. Such mental engagement leads to constructing original knowledge or new knowledge representations (Norman, 1993).

We should carefully study the transactions that learners make when they interact with cognitive tools and develop their cognitive partnerships because cognitive tools are intended to leave the decision-making and higher-order thinking on the part of the learners, not to provide them with instruments that allow them to accomplish tasks and solve problems mindlessly. For example, students using statistical analysis packages as cognitive tools sometimes mindlessly accept results that are preposterous.

Another issue facing researchers focused on educational applications of cognitive tools is communicating their ideas of cognitive tools to practitioners and ensuring that these tools are used appropriately in the classroom. Salomon and Almog (1998) argued that no matter how we try to transform the way students learn in classroom with new technologies, the established classroom structure usually undermines the intended use of the tools (e.g., instead of using a tool such as CADCAM software for complex tasks, students are taught one way of using the tool step-by-step to accomplish routine tasks). Admittedly, the ill-structured nature of activities using cognitive tools sometimes makes it harder to manage classrooms and assess student performances, thus making appropriate use of them more difficult (Resnick and Ocko, 1991).

The disintegrated research approaches

Significant research and development have been done under the broad umbrella of cognitive tools in the last decade with various research approaches. Studies of cognitive tools vary widely in the sorts of tools used, e.g., simulation of medical experts' activities (Lajoie, 1993) and employment of scientific visualization tools (Schwartz et al., 2000). Using various research methods, such as tests, observations, interviews, and think-aloud protocols, researchers have attempted to find what significance these tools have in student learning. Contemporary learning theories extend the property of knowledge and performance outside an individual's mind (Brown et al., 1993). Some research studies on computers in education (e.g., Azevedo et al., 2004) rigorously examine the complex cognitive and metacognitive processes of learning; but such detailed attempts to capture the complex interrelationships between the performances of computers and learners are still difficult to find.

Researchers have confronted similar issues in ways that may have limited progress in the development, research and application of cognitive tools. Erkunt (1998), in reporting his study about a cognitive tool, concluded that the concept of cognitive tool is useful but vague, thus making related empirical research difficult to describe. The research approaches applied to it have not been sufficiently differentiated from other kinds of educational research. Computer applications designed or adopted as cognitive tools have been investigated in terms of what learners were able to accomplish during and/or after learning with the tools. However, the relationships between learners and tools, i.e., their roles as intellectual partners and partnering processes, were not adequately addressed in most research studies. It is hard to capture the partnering process within a short period of usage time and often not possible to observe and report the process with conventional research approaches. As a result, the principles of using computers as cognitive tools have not been realized at any level of education. New researchers in cognitive tools who wish to contribute to their development and application, thus, should adopt research methods that can take complex interrelationships into account.

A need for an integrated framework

There is a clear need to define an integrated framework for the study and practice of cognitive tools. This framework should be conceptually coherent to foster more successful design, application, and research. Such a framework would allow designers and researchers to specify what features of tools are used or not used and how they are used for certain cognitive tasks. The practical issues of cognitive tools would then come down to developing appropriate learning activities for higher-level cognitive tasks, so that the tools are used in ways that neither give learners easy answers nor frustrate them with unnecessarily complicated features. Learners could be challenged with authentic tasks, which require them to engage in the types of discourses and problems similar to those of experts in the world, such as historians and scientists (Savery and Duffy, 1996), and wherein cognitive tools are actually needed to accomplish them.

In light of this need, the primary purposes of this paper are:

1. to critically review and identify the potential benefits and weaknesses of the previous research and development of cognitive tools;
2. to propose an integrated framework for research and development;
3. to redefine cognitive tools and examine renowned learning technologies with the alternative framework;
4. and to prescribe an agenda for research and development to maximize benefits and overcome weaknesses.

In short, we intend to develop the meaning of the cognitive tool beyond its abstract conception, in order to improve research and practice related to computers as cognitive tools. We first describe two underlying learning theories (distributed cognition and expertise), present the new framework, and then explore the potential for advancing cognitive tools based on this new perspective.

Conceptual background of cognitive tools

Inquiries into how learners construct their knowledge require as much attention to learning processes as to learning outcomes. Theories concerning human knowledge and cognition, such as constructivism and distributed cognition have been adopted by many researchers investigating cognitive tools in education. Constructivism is a theory of how people gain knowledge about the world, which posits that people come to know about the world by imposing their own meanings on it (Duffy and Jonassen, 1992; von Glasersfeld, 1995). There is no one right way to view the world according to the tenets of constructivism, and thus a constructivist learning environment should draw attention to multiple perspectives and diverse ways of viewing and solving problems. Constructivist approaches emphasize learners' active participation in meaningful activities (tasks to complete or problems to solve) that foster building new knowledge and richer understanding (Phillips, 1995; Duffy and Cunningham, 1996; Salomon and Almog, 1998; Herrington et al., 2003). Distributed cognition is a view that cognition does not reside only in one's mind, but that cognition is distributed among people, artifacts and symbols during thinking, reflection, and learning (Salomon, 1993a). The theory of distributed cognition provides insights into how learners use their environment and its sub-components as integral parts of their learning process (Salomon, 1993c). The attempt to comprehend how learners use cognitive tools as an integral part of their learning process is a primary focus of this paper.

Distributed cognition has not been conceived and described consistently. Focusing on the social aspects of human thinking, some theorists agree with Vygotsky (1978) that cognition and activity are distributed basically among people but mediated by signs and tools (e.g., Resnick et al., 1991; Wertsch, 1991; Hutchins, 1995). On the other hand, others consider that cognition resides not only in persons but also in signs and tools, conveying cultural meanings and history (Salomon, 1993c; Lebeau, 1998).

Another major difference among views on distributed cognition is regarding whether or not the distribution is an absolute characteristic of human thinking. Some suggest that cognitive activity is always distributed in some respects even when carried out by a person in isolation by virtue of the language used (e.g., Cole and Engeström, 1993; Pea, 1993; Wertsch, 1991). Others recommend making a distinction between individual cognition and distributed cognition (Brown et al., 1993; Perkins, 1993; Salomon, 1993a). Common to these views is the notion that human cognition relates to the environment outside of an individual.

Kinds of distribution

There is some agreement among researchers that there are social, symbolic, and physical (or material) distributions of cognition (Perkins and Grotzer, 1997; Salomon, 1993a). Social distribution of cognition is often exemplified in workplace settings where the dynamics of team thinking and group decision making are critical (e.g., Derry et al., 1998). Symbolically distributed cognition includes signs, symbols, language, and representation that make our everyday thinking possible. Some researchers do not include symbolic distribution in their dimensions because symbols are almost always embedded in other kinds of cognition (e.g., Pea, 1993; Perkins, 1993; Karasavvidis, 2002). Symbols used for mathematical multiplication problems (i.e., the two numbers, the position of two numbers, the sign × for multiply, and the line drawn underneath the arrangement of these symbols) have their own culturally provided meanings and convey the cognition of the person who designed the problem (Wertsch, 1998). Physical distribution includes everything visible or tangible, ranging from pencil and paper to artificial intelligent machines. A popular example of physical distribution is the use of a calculator or abacus for mathematical tasks.

A cognitive activity usually reflects some aspects of all three cognitive distributions: social, symbolic, and physical. For example, brainstorming for ideas as a team exemplifies social distribution of cognition among people. Drawing a diagram on the board to visualize their discussed ideas reflects their dependence upon the symbolic and physical distribution.

Distributed cognition and cognitive tools

People working together affect one another's thinking and behavior according to social structures and norms. Symbolic and physical means affect our thinking in different ways from people. The symbols that we use have the most direct relationship with our internal mental representations. Physical distribution usually involves some change in artifacts as the result of the thinking process (e.g., the position of beads on an abacus) (Vygotsky, 1978). When using physical means and representations for mental processes, they become a part of the interactions and outcomes of thinking (Pea, 1993; Salomon, 1993a). Sometimes, the involvement of novel symbolic and/or physical means in mental process changes the very nature of the activity (Cobb et al., 1991). In this sense, computers as symbolic and physical means, enhance or extend our cognitive powers, through speed and accuracy in processing information and representations, off-loading laborious tasks for higher-level thinking, and decision-making and problem-solving based on the result of the computer processing. Statistical analysis software, for example, has changed the nature of data analysis activities to allow statistics to become a part of the interactions and outcomes of diverse human decision-making processes.

This theory is closely related to the way constructivists think about the role of the computer in the process of learning. The computer is no longer perceived as a mere delivery medium, but as a technology that has unique capabilities to complement a learner's cognition (Kozma, 1991). Salomon et al. (1991) emphasize this cognitive process by making an important distinction between effects "with" and effects "of" technology. Effects "with" technology result in enhanced intellectual performance during learning by the physical distribution of cognition to the technology. On the other hand, effects "of" technology are evidenced by the cognitive "residue" that remains after completing a cognitive task using technology (Salomon et al., 1991).

By distribution, it does not mean that a cognitive activity is divided into parts and assigned to the computer so that learners could think or work less. Rather, distribution implies a dynamic state of cognition that is extended by the capabilities of the computer. Cognitive tools should not take over important human thinking such as decision-making, but perform those cognitive tasks that may prevent learners from engaging in deeper thinking (e.g., doing repetitive calculations when calculation itself is not the important part of the task) or help learners think outside of box (e.g., making connections between boiling water and physics rules by using special software) (Pea, 1993; Salomon, 1993a). By extending human cognition, cognitive tools change the nature of activities and open possibilities for new activities. Moreover, they potentially transform our cognitive structure and processes (Salomon and Perkins, 1998).

Tool affordances

The impact of computers in education rests in defining them as thinking partners that extend human cognitive capabilities beyond mere delivery media (Salomon et al., 1991). The theory of distributed cognition provides an agenda as to how cognition should be distributed among participants of an activity, focusing on the novel opportunities gained by using computers in learning.

Pea (1993, p. 51) employed Gibson's notion of "affordances" as properties of tools that determine their usage. Affordances in distributed cognition are the possibilities that symbols and artifacts provide in the distributed relationships. Those affordances always exist, but not all of them can always be used without the initiation and desire of the person participating in the distribution (Pea, 1993). On the contrary, we sometimes become so accustomed to being dependent upon some symbols and artifacts (e.g., calendars in both symbolic and physical forms) that their roles for our cognitive activities are not even recognized, attributing the performance only to ourselves (Pea, 1993; Karasavvidis, 2002). Technological affordances, the kinds of cognitive functions represented (or possible to represent) in the design of a tool, are intended to support certain tasks through the designers' reasoning and decisions, reflecting social norms and cultural meanings (Pea, 1993; Karasavvidis, 2002). Ultimately, how the technology is used depends on both the intentions of the designers and the users (Moore and Rocklin, 1998).

In summary, the theoretical assumptions about cognitive tools based from the distributed cognition view are:

1. Cognition is distributed between learner(s) and a cognitive tool;
2. The way in which cognition is distributed is first determined by the intentions of tool designers, i.e., tool affordances; and
3. It can then affected by how the learners decide to use it in specific situations.

Expertise and technology

The theory of distributed cognition highlights the roles of tools in assisting the cognitive tasks of learners, but ideas about how we should decide what to include as functions of technology, how those functions could work with learners, and how we should study these have not been fully established. The theory of expertise provides another dimension that complements the concept of cognitive tools by clarifying perspectives on the nature of excellent performances. Within the field of instructional technology, theories of expertise have been discussed and employed mostly in areas such as intelligent tutoring systems and expert systems wherein computers are used to model expert processes (e.g., Anderson et al., 1995; Feltovich et al., 1997; Conati and VanLehn, 2000; Aleven and Koedinger, 2002). In the following discussions, we adopt this theory to go beyond simply acknowledging the distributed nature of a particular learning system to exploring how that system develops and how we can support and design effective learning systems. Expertise theory is discussed in terms of the components of expertise, how they are developed, and how expertise is defined when technology is involved in order to describe and interpret the relationship between cognitive tools and learners.

Expertise is sometimes characterized as a standard of an expert performance in a certain domain (Ericsson and Smith, 1991), or as a relative degree of excellence for a given activity (Salthouse, 1991). Most research studies have focused on expert performances in professional domains, and tried to find the relatively stable characteristics of experts in performing outstanding behaviors (Ericsson and Smith, 1991). A broader view of expertise, more applicable to the discussion here, contends that everybody has some degree of expertise with respect to our everyday activities (e.g., Sloboda, 1991; Brown et al., 1993; Carlson, 1997).

Assuming a mastery level of performances, conventional expertise approaches attempt to describe the characteristics of domain-specific competences (Ericsson and Smith, 1991; Glaser, 1996). Researchers examine the knowledge structure and cognitive processing of experts during task performance and compare them to those of novices. (See Olson and Biolsi (1991) for more detailed analysis of expert knowledge.) More recently, researchers have recognized the importance of developmental conditions and continuous improvements of expertise and started investigating processes of skill acquisition with exhaustive approaches, such as analyzing the life histories of virtuosos to find general patterns of development (Ericsson and Smith, 1991; Glaser, 1996). Although the theory of expertise is still incomplete, especially in its explanation of early phases of skill acquisition as well as acquisition of mediating mechanisms (Ericsson, 1996), several decades of research have pioneered a refined comprehensive understanding about the nature of expertise: its kinds, structures, and development.

Kinds of expertise

Experts usually use several kinds of expertise in performing tasks; different kinds of expertise interact with each other and contribute to the process of task performances. Most commonly, distinctions are made between domain expertise and general expertise. Domain expertise is more specific to the knowledge and processing strategies of a certain domain (such as medicine) whereas general expertise (such as creativity) can be transferred and used across different domains. After decades of debate about which expertise is more important in actual performances, it is concluded that they function interdependently in close relationships (Perkins and Salomon, 1989). Schunn and Anderson's (1999, 2001) studies show that expertise in scientific reasoning transferred to other scientific domains. Certain domain expertise, such as literacy, often interacts with other domains of expertise and affects the performance of tasks (Holyoak, 1991; Scardamalia and Bereiter, 1991). Patel and Groen (1991) further specified the kinds of expertise as threefold in nature which they labeled generic expertise, specific expertise, and domain-independent (or general) expertise. They classified domain expertise into two categories (generic and specific) in relation to the specificity of knowledge and skills within a domain. As there is more and more specialization within a domain of expertise, a person may possess only generic expertise of the domain, or both generic and specific expertise (Patel and Groen, 1991; Ericsson and Charness, 1994).

Structure of expertise

In the performance of tasks within a domain, there seems to be some structure that characterizes expertise. The elements of structure can be summarized as knowledge, function, and representation, which interact with each other during task performances. The nature and the purpose of knowledge in a field affect how knowledge is organized and processed for effective performances (Anzai, 1991). The knowledge that experts process during practices ranges from more deductive knowledge (e.g., rules and formulas) to more inductive knowledge (e.g., information about exemplars) (Patel and Groen, 1991). When acquired knowledge is organized in a coherent way (i.e., internal representation of knowledge), the cognitive functions, such as recognizing structures or patterns and making inferences, are made easier (Glaser, 1996; Winn and Snyder, 1996). Some of the functions, such as anticipating results and evaluating performance, not only mediate performance but also promote improvement (Ericsson and Charness, 1994; Ericsson, 1996). The ability to use external representations of knowledge and processes also plays an important role in the performances of many domains (e.g., Anzai, 1991). Experts generate complex representations about the problems they encounter, which provide images to support constant reflections on and improvements in their decision making and actions (Ericsson, 1996; Glaser, 1996; Winn and Snyder, 1996). Knowledge, function, and representation work together with significant roles in the performance of experts and their development of expertise.

Development of expertise

To develop expertise, one must face the problems that challenge one's current level of knowledge and competences. Not only to develop expertise and become an expert but also to remain an expert, one should extend competence levels (Scardamalia and Bereiter, 1991). The time a person spends in a field is critical in the development of expertise, although mere exposure should be differentiated from learning and practice (Ericsson and Smith, 1991). The results of studies show that intensive training had much more significant effect on accuracy in clinical judgment than extended experience (Camerer and Johnson, 1991). Development of expertise thus requires a long period of active learning with deliberate practice and learning strategies (Perkins and Salomon, 1989; Ericsson et al., 1993; Ericsson and Charness, 1994).

Understanding how learning activities change over the development of expertise provides an important foundation for education (Glaser, 1996). Research indicates that learners go through the process of gaining knowledge structure, problem-solving strategies, and automaticity during the development of expertise (Keating, 1990; Schneider, 1993; Winn and Snyder, 1996). In structuring their knowledge, novices first make cognitive efforts to understand the task and find important information, and then organize their knowledge into a more accessible structure (Schneider, 1993). This internal structure of knowledge is often revealed and enhanced by their use of external representations, which is an essential skill in many domains of expertise (Patel and Groen, 1991). They then learn to use these representations more efficiently with relevant information in a problem (Patel and Groen, 1991).

Novices approach problems with strategies that are based primarily on concrete information, and then they use more and more abstract reasoning as they gain more expertise. Novices rely on the surface features of the problem, commonsense knowledge and trial-error approaches because they do not have enough domain-specific knowledge base and expertise (Anzai, 1991; Patel and Groen, 1991). Gaining more expertise, the person starts to use what is called a general or weak method. This method uses diagnostic reasoning, data-driven reasoning, observation, and problem reduction instead of starting with underlying principles (Anzai, 1991; Patel and Groen, 1991). Experts approach problems with a specific (or strong) method. They work on the problems with working hypotheses and rely on systematic representations of the information in the problem in relation to their domain-specific knowledge structure (Anzai, 1991; Patel and Groen, 1991). Experts select and focus on only important and relevant information in the problem and often switch between general methods and specific methods depending on the problem (Anzai, 1991; Patel and Groen, 1991; Scardamalia and Bereiter, 1991). It is almost impossible to make conscious efforts to switch between different levels of knowledge and strategies during the performance of expert level tasks. For many experts, some of these processes are automatized by their repeated performances on different problem-solving tasks, enabling them to use their cognitive resources to deal with the novel aspects of the current problem situation (Schneider, 1993; Winn and Snyder, 1996).

In the earliest research studies, expertise was regarded as a separate property from everyday activities; it was researched in isolated laboratory settings to tease out problem solving processes on a set of standardized tasks. Realizing that individual expertise cannot be fully understood without understanding the environment of the individual, expertise researchers began to look at the dynamics of interactions with environments in the development of expertise (e.g., Keating, 1990; Patel et al., 1996; Winn and Snyder, 1996). Today, many domains of expertise cannot even be understood without studying the experts' use of external aids. These external tools often play a significant role in the work of experts even in studies conducted in isolated labs. Anzai (1991), studying physics expertise, examined the subjects' use of diagrams as external aids and cognitive representations, and the relationship between the use of diagrams and the level of expertise. Physics diagrams worked as catalyses for information recall as well as tools for computational efficiency and inferences (Anzai, 1991). Simulated computer environments are often used in studying the performance of experts to accommodate some real-world complexity to the experimental setting (e.g., Dörner and Schölkopf, 1991).

Recent expertise studies have extended their research to natural contexts (e.g., Dunbar, 1995; Patel et al., 1996). Dunbar (1995), for example, examined complex cognitive processes in the real world in his investigation of scientific reasoning and discovery, and recognized the importance of using analogies in the social context of science.

Another line of research in expertise involves analyzing expert reasoning and building computational models to perform complex tasks (i.e., artificial intelligence and expert systems). Studies of expert reasoning structure to make computational models are very similar to studies of experts' cognitive processes (Patel and Ramoni, 1997). These machines are programmed to recognize patterns and perform tasks through sets of production rules (Patel and Groen, 1991). Researchers recognize that there is a standard way of reasoning requiring deliberate and precise efforts that can be completed by machines without exhaustion or error, but insist that novel and constructive ways of reasoning can only come from human beings (Dreyfus and Dreyfus, 1986; Hoffman et al., 1997). Researchers suggest treating machines as having different objectives from us and imposing the roles that are appropriate for them (Dreyfus, 1992). In this way, experts are not replaced by the computers, but empowered by them to make better use of their expertise (Dreyfus and Dreyfus, 1986).

Expertise is not only shaped by the dynamic social context and artifacts in the setting but also redefined by changes in the ways we do things (Patel et al., 1996; Feltovich et al., 1997). The expertise of physicians from 50 years ago looks very different from the expertise of present day doctors with advances of medical techniques and technology as well as new specialized areas in the medical field. Experts in our society rely on the environment and adapt to the changes of its properties; they are "codefined by context" (p.182, Stein, 1997). What we call "expertise" is now being redefined not as a sole property of an expert, but as a combined whole with the environment and artifacts that expert is dependent upon.

From the theory of expertise, we can summarize the assumptions that we make about human performances:

1. Expertise can be classified as general, generic, and specific;
2. Structure of expertise can be examined with its components, i.e., knowledge, functions, representations;
3. As individuals develop expertise, their knowledge structure and problem-solving strategies improve, and they gain automaticity on some of their processes;
4. Expertise is defined with the external aids that individuals use for their tasks, becoming part of their expertise.

Distributed cognition and expertise coming together as one lens

Netchine-Grynberg (1995), seeking the origin of cognitive tools, recognized three main characteristics of cognitive tools: (1) they are culturally formed and transformed for the functions of real-world human activities, (2) they enclose semiotic structures and provide the means to construct representations that guide actions and ultimately form and activate human cognitive structures during real-world activities, and (3) they are goal-oriented and instrumental, forming cognitive relationships and mediating actions between humans and the environment. Individuals, in this perspective, never directly confront reality, but they experience and internalize it through activities using cognitive tools (Netchine-Grynberg, 1995). Although the term "cognitive tool" is an important construct for researchers as well as practitioners, the idea not only has not been well-advanced but also somehow has lost its origin in the course of adopting it for computers in education. The term is sometimes used as a catchphrase and "sold" to teachers as a better way of using technology in the classroom without clearly communicating its implications for instructional methods and the teacher's role.

The premise of putting distributed cognition and expertise theories together is that the assumptions of the two theories would specify the meaning of cognitive tools, which has remained too vague for researchers and practitioners to make it useful for their practices. We will return to the above origin of cognitive tools, reinterpret it through the lens of the two theories, and uncover what it means for enhanced research and practice for cognitive tools in education.

The meaning of cognitive tools

Recent studies on expertise include the distributed cognition perspective, stressing the importance of the role of environment in the cognitive activities of experts (e.g., Lebeau, 1998; Patel et al., 1996). Research and development of expertise and distributed cognition in terms of technology comes together to an important point at this juncture: they both emphasize the significant role of technology in extending human abilities instead of replacing them. Researchers supporting distributed cognition, however, see technology from a very different angle from researchers of expertise, and even look at different kinds of technology. In the theory of distributed cognition, technology is envisioned in a more general level, existing as one of the various resources in the distribution of cognition. Overlaying the theory of expertise upon distributed cognition, individuals, environment and tools are viewed as a system of performance, bringing their qualities and expertise to the situation and interacting with each other (Salomon, 1993a; Patel et al., 1996).

The expertise view of technology adds specificity to the distributed notion in that the technology becomes one of the most important assets of the involved activities. With the basic assumptions that cognition is physically distributed to technology and that expertise is co-defined with experts' tools, a cognitive tool can be regarded as having some kind of expertise that allows cognition to be distributed to it, forming a joint system of learning (see Table 1). We can redefine cognitive tools for learning with this added expertise perspective:

> Cognitive tools are technologies that learners interact and think with in knowledge construction, designed to bring their expertise to the performance as part of the joint learning system.

Table 1. Theoretical assumptions and proposed conceptual constructs of cognitive tools

Distributed cognition	Expertise	Cognitive tool
1. Distribution	1. Expertise kinds	1. Tool expertise kinds
2. Distribution by design	2. Expertise structure	2. Learner-tool expertise structure
3. Distribution in action	3. Expertise development 4. Expertise co-defined	3. Learner-tool expertise development

Learning with technology, when considered with these two theories together, is no longer performed solely by the learner but as a joint learning system, comprising at least learner(s), tool(s), and activity.

Cognitive tools and expertise of joint learning system

Several conceptual constructs about cognitive tools accompany this new definition based on the assumptions of the two theories (Table 1), reflecting the original characteristics of cognitive tools described by Netchine-Grynberg (1995). First, cognitive tools can be classified with the human expertise classification because the attributes of distributed cognition is first determined by its design and the tool should be classified according to its purpose. In other words, if we regard the kinds of expertise as representing the layers of capabilities for human performances, the tools that extend those capabilities should be classified in the same way.

In the same line of thought, cognitive tools form a joint learning system when the distribution is in action with the learner(s). The way the distribution is structured within the system as well as the way the expertise of this joint learning system develops should be examined in the same way we have examined human expertise (second and third constructs in Table 1). There are two kinds of designs that have major influence on the structure of distribution: the design of tools and the design of activities. The distribution of cognition is structured by implicit characteristics of the cognitive tool (e.g., determined by the software designer) as well as by the explicit aspects of current activities (e.g., determined by the classroom teacher) (Pea, 1993).

These constructs reflect the original cognitive tool idea of capturing realities, having semiotic structure, and mediating human activities for specific purposes. We also need to consider the specific purposes of the tools and what learning activities they are mediating because, unlike real settings, activities are designed in educational contexts. In the next two sections, we discuss these constructs (kinds of cognitive tools and their activities, and development of joint learning system expertise) in detail.

Expertise in the tool and the activity

The term "cognitive tools" is used for explaining many different abstract as well as concrete entities (e.g., both human language and physical calculators are considered cognitive tools). Cognitive tools for learning have been classified based on their different characteristics and purposes. After analyzing the different purposes of tools, Jonassen and Carr (2000) suggested some classes of "mindtools" as semantic organization tools (e.g., databases and concept mapping tools), dynamic modeling tools (e.g., spreadsheets and microworlds), visualization tools (e.g., MathLab and Geometry Tutor), knowledge construction tools (e.g., a multimedia authoring tool), and socially shared cognitive tools (e.g., computer conferencing and computer-supported collaborative argumentation).

Over the two different volumes of *Computers as Cognitive Tools* (Lajoie and Derry, 1993a; Lajoie, 2000), the distinctions among different tools shifted to fit the current pattern of emerging learning paradigms and the corresponding development trend of computer programs. In the first volume, Lajoie and Derry (1993a) categorized the research accounts into modelers (e.g., TAPS; Derry and Hawkes, 1993), nonmodelers (e.g., HyperAuthor; (Lehrer, 1993), and the ones merging the two (e.g., DARN; Schauble et al., 1993). Modeling here meant that the computer program models students' thinking processes and diagnoses their performances. In the second volume, Lajoie (2000b) divided the chapters between the tools supporting knowledge-building activities (e.g., SCI-WISE; White et al., 2000) and the tools supporting new forms of knowledge representations (e.g., DNA; Shute et al., 2000).

Other researchers have imposed their own theoretical framework for categorizing cognitive tools. Salomon (1993b) suggested that there are two kinds of cognitive tools based on the theory of distributed cognition. The first kind represent performance-oriented tools that learners use to jointly make products with the tools (e.g., Freehand, a graphics program), and the other kind are pedagogic tools that support learners' cognitive growth (e.g., Writing Partner; Salomon, 1993b). Whether empirically or theoretically oriented, the existing classifications do not seem to well-characterize computers specifically as cognitive tools in ways that imply their usage in real contexts (or of similar tools in the world). Salomon's (1993b) suggestion that cognitive tools should be evaluated for their potential affordances of cognitive activities and promotion of learner abilities was reflected to some degree in the detailed discussions presented by the aforementioned scholars, but not often in their classifications. There is an obvious need for a classification system that may offer those implications and provide a better basis for examining the interactions between the tool and the learner.

The remainder of this section presents a different way of and a rationale for classifying cognitive tools for learning. Classifying cognitive tools with their potential expertise and distributed structures in carrying out activities provides insight into their detailed characteristics as cognitive partners. Tools are discussed in terms of their interactivity with learners and specificity in their purposes. The prominent computer tools in education are reexamined, and the ways cognitive tools relate to learners are reconsidered through the specific lens that theories of expertise and distributed cognition provide.

Tool interactivity

Tools vary in the interactivity they afford with users, ranging from one--way, whereby technology is used as a mere delivery medium of information, e.g., multimedia presentations, to reciprocal interactions, wherein technology actually participates in the cognitive activity of individuals, e.g., a DNA modeling program. Somewhere in the middle ground is the cognition distributed for a division of labor to offload some tasks or to prevent human-errors with technology, e.g., a calculator or a spell-checker (Perkins, 1993; Salomon, 1993a). Interactivity usually depends on the technology itself, but it is also affected by how the technology is used by individuals and what kinds of activities it is used for.

As physical tools make us physically stronger (e.g., hammer) or faster (e.g., bicycle), computer tools make us smarter, augmenting our cognitive capacities (e.g., speed of processing) (Lave, 1988; Norman, 1993; Pea, 1993). In the ideal level of interaction, technology changes the nature (i.e., process and product) of cognitive activities, allowing individuals to think with the technology in a way that was impossible without it (Pea, 1993). Theories of expertise and distributed cognition converge at this higher level of interactivity, where technology plays an essential role for cognitive activities. Tool expertise mainly characterizes the tool itself, but at the same time implies potential user activities. Ideally, cognitive tools, being considered as "partners," should be characterized by their reciprocity, remaining at the right end of the interactivity continuum.

A cognitive tool, in our definition, is a cognitive partner that interacts with learners to construct knowledge, bringing its expertise to activities. As a tool, it should be flexible enough to be used for various activities and open to the mindful and creative growth as a joint system with learners. Scholars of distributed cognition, however, suggest that there are certain properties that cannot and should not be distributed to technology, e.g., higher-order thinking (Perkins, 1993). The machine can process a set of rules to perform certain tasks, such as making a representation, tracing the learner's use of the program, retrieving certain stored knowledge and representations, but cannot understand the meaning of those representations and activities (Salomon, 1993a). The roles of the tools should only be to help humans in meeting cognitive challenges. As argued by many researchers (e.g., Perkins, 1993; Salomon, 1993a), cognitive tools should not take over, but require higher-order thinking from learners for task completion, thus fostering creativity in learners.

Another important property that ultimately humans should perform is executive functions for activities (Perkins, 1993). In the course of constructing knowledge through inquiry and problem-solving, individuals should decide what to do and where to go instead of the machines making decisions. Adopting the view from expertise theory about relationship between person and technology, technology can only have roles that can empower and augment higher-order cognitive functions. Technology for experts is an instrument that supports, but not usurps, inquiry, redefining what it means to be an expert (Stein, 1997). Cognitive tools for learning, therefore, should assume lower executive functions, such as executing rules, and let learners make the most important decisions during activities.

Tool specificity

The way cognitive tools are classified here highlights the way expertise is classified in the literature. As introduced earlier, Patel and Groen (1991) categorized human expertise in three levels considering its specificity: domain-independent (general) expertise, generic expertise, and specific expertise. These kinds of expertise can be used to understand what kind of roles tools play in their partnerships: general cognitive tools that have qualities independent of specific domains to support various activities; domain generic cognitive tools that bring in basic characteristics to support various activities in a rather broad area of a domain; and domain specific cognitive tools that deal with more specific concepts in domains with representations and knowledge specific to narrower topics. The more specific a cognitive tool is, the more in-depth activities it affords covering less variety of content; the more general it is, the more variety of activities and contents it affords. There is no superiority among tools with different levels of specificity because each serves different purposes. A graphics package such as Photoshop is invaluable for the learner wishing to create artistic visual models of cell structure, but of little utility to the learner who desires to compute complex equations of planetary motion.

The three primary elements of expertise structure, i.e., knowledge, function, and representation, then should be used to examine the characteristics of cognitive tools. Embedded knowledge in the tools can range from widely accepted facts to abstract rules (Anzai, 1991; Patel and Groen, 1991). Functions can vary from simple information search and rule execution to complex decision-support (Perkins, 1993; Ericsson and Charness, 1994). Representations can be more concrete (isomorphic) or more abstract (symbolic). Depending on the specific activities carried out within a domain of study, certain levels of representations are more beneficial than others. Geographers require precise visual representations of spatial relationships whereas anthropologists may be satisfied with rich narrative representations. Technology can afford various ranges of representations that can be manipulated by learners (Salomon, 1990).

A computer chess game, for example, has specific expertise in chess with knowledge about chess rules and the patterns of chess moves, functions of recognizing patterns and making moves, and visual representations of chess board and moves. The Writing Partner (Zellermayer et al., 1991) was designed to become a cognitive partner of children learning to write, as in physical distribution of cognition. This program supports meta-cognition about the writing process, so that the young writers can think with the Writing Partner during the process. Seen from the kinds of expertise, the Writing Partner seems to have generic expertise in writing strategies (because it is not a specific kind of writing, such as writing a scientific article) with knowledge about detailed strategies of writing and the function of posing questions to the writer. A computer-supported intentional learning environment (CSILE) (Scardamalia et al., 1989) provides a space for collaborative knowledge construction within an online environment. CSILE supports physical distribution of cognition as well as asynchronous social distribution of cognition, dramatically changing the nature of knowledge construction activity. CSILE can be used across many domains of knowledge so that it seems to have domain-independent expertise—learners bring most of the specific knowledge to work with—with functions of storing and organizing data and representations of concept relations.

We first classified the tools into three different categories according to the three levels of expertise that are embodied in the tools (General, Generic, and Specific). Regarding the expertise embodied in tools, we considered their weighted elements that constitute the structure of expertise as to whether the embodied knowledge is more rule-based (deductive) or case-based (inductive) and whether the embodied representation is more symbolic or isomorphic. We then put them into different columns depending on where they are in their functional properties (see Table 2). The functional properties of computer programs, especially their executive functions, determine their interactive relationship with learners. We scaled the degree of executive functions that computer programs provide with six different levels: lowest, lower, low, high, higher, and highest. The lowest is for those communicating with users only with the same symbol system, such as program languages, which requires very high analytical and logical thinking and with which users make decisions about everything other than the symbol system itself; the lower for those executing learner-created rules with learner-created objects; the low for those having more embedded rules than the lower. We scaled the high for those guiding the decisions of learners; the higher for those interpreting learner responses and behaviors and making decisions for learners, or providing predetermined content with no particular order; and the highest for those diagnosing individual learners and making decision without informing learners, or providing sequenced information presentations without learner inputs and controls.

In Table 2, examples of educational programs are presented with various degrees of executive functions. This table demonstrates the relative positions of educational programs that we classify as cognitive tools on the continuum. The heavy lines are drawn around boxes of those we perceive as cognitive tools. We maintain that cognitive tools can vary in their expertise level, but higher-order thinking and executive functions should be left more for the learner, staying at the *low* and *lower* levels. The dotted lines are used for the boundaries in order to indicate that many educational programs often contain characteristics of different levels. A person's expertise

Table 2. Examples of different kinds of cognitive tools and their relative positions

Expertise (E) knowledge (K) representation (R)	*Executive function*					
	Lowest	*Lower*	*Low*	*High*	*Higher*	*Highest*
		Cognitive tools: higher-order thinking and executive function more by the learner				
E: General K: symbols R: symbolic		Authoring tools	Productivity tools	Meta-level programs	Production wizards	
E: Generic K: rules R: symbolic	Programming languages	Microworlds	Visual representation tools	Intelligent agents; expert systems	Intelligent tutoring systems; multimedia environment	Computer-based tests; information presentations
E: Specific K: rules/cases R: isomorphic		Manipulative tools	Simulation tools			

does not have clear boundaries among different levels and a person can have multiple levels of expertise at the same time. Likewise, the position of a particular tool could be variable depending on how other researchers characterize certain tools or how instructional designers and educators decide to employ them in practice. In the next four sections, we first discuss these cognitive tools in more detail using the three levels of expertise, and then we describe the characteristics of other kinds of educational programs in comparison to cognitive tools.

Domain-independent (or general) cognitive tools

Some cognitive tools basically have general qualities independently of domains. The descriptors of each row in Table 2 (i.e., knowledge and representations) are not about the learner's gaining knowledge or resulting artifacts, but about what the tool holds in order to interact with the learner. Domain-independent cognitive tools typically use certain symbol systems and symbolic representations to communicate with learners during the process of building knowledge and making products. When the degree to which a tool performs an executive function is relatively low, there are more possibilities for engaging in various forms of activities and creating different types of products. Authoring tools are an example of cognitive tools with low executive functions, and productivity tools are an example of one with more embedded rules for output products.

Authoring tools are alternatives for programming languages whose interfaces are scaffolded by symbolic metaphors, such as index cards, stages, frames, and trees. Productivity tools, such as databases, spreadsheets, and concept-mapping tools, are programs originally developed to increase workplace productivity by organizing knowledge and information in a more accessible manner. Researchers saw the values of using these two kinds of general tools for educational purposes and suggested using them as cognitive tools for learning whereby learners become designers who construct "knowledge representation" products with the tools (Jonassen and Reeves, 1996). Erickson and Lehrer (2000) studied students in seventh grade using an authoring tool called HyperCard (using the metaphor of index cards) throughout a school year and described students' processes of understanding the role of links in their hypermedia products and how their understandings were reflected in their design of HyperCard stacks. Authoring tools can be used flexibly by users for creating various kinds of knowledge representations such as a multimedia presentation or a website.

Productivity tools, on the other hand, can usually afford only certain kinds of representations (e.g., concept-mapping tools afford the creation of maps and outlines). Productivity tools are highly accessible to many classroom teachers and can be used for knowledge organization tools in many different disciplines. Concept-mapping tools have been extensively studied by many researchers and found to be very helpful not only for individual thinking activities, but also for group decision-making processes or knowledge-building activities in face-to-face classes or over the Internet (e.g., Jonassen, 1993; Hewitt and Scardamalia, 1998).

Domain generic cognitive tools

Some cognitive tools possess basic characteristics to support various activities across a broad area of a domain. These tools are more prevalent in science and mathematics where representation of complex knowledge is very important in problem-solving processes. Generic kinds of cognitive tools have the rules that underlie a domain, such as physics and chemistry, and usually produce symbolic representations, such as graphs and other visualizations of data. With some executive function embodied, generic cognitive tools have more structure for what is expected from the learners and for the representations. With even lower executive functions, learners construct this structure out of the variety range of possibilities. The example for the latter is microworlds, and for the former are visual representation tools.

StarLogo is a well-known microworld that helps learners to explore systems dynamics. StarLogo operates according to the rules created by learners to produce a dot or collection of dots on the screen interacting in the represented world (Resnick, 1996). Learners create representations of real-world systems by deciding how which system elements work in what ways within StarLogo. Other generic cognitive tools start with certain sets of visual representations to enable students to approach problems (e.g., Kozma, 2000a). To learn about dynamic systems, Stella requires learners to specify factors that stimulate the system changes so that it generates certain visual representations, such as diagrams and graphs (Resnick, 1994).

Other tools, such as Model-It and MathWorlds, combine these two levels of functionalities. Using Model-It, learners can create various levels of complexity within dynamic systems, such as stream ecosystems and human body systems, by importing graphics to contextualize their models and defining the factors and the relationships among components of a system (Metcalf et al., 2000). Learners test and evaluate the model using the software's specific graphing tools.

MathWorlds provides an environment in which learners define how interacting animated characters' motions are connected using graphs that can be manipulated (Roschelle et al., 2000).

Domain specific cognitive tools

Cognitive tools that deal with concepts in specific domains use more concrete representations and encompass more knowledge about individual cases in addition to any rules that govern them. These tools are similar to the domain generic cognitive tools, but they deal with more specific content areas. Some of these tools with lower executive functions allow learners to create their own cases with which they can work, whereas others with more structure provide choices and/or a database of cases. An example of the former is the manipulative tool, GenScope, and of the latter is the simulation tool, MicroObservatory.

GenScope, specifically designed for the domain of genetics, allows students to manipulate objects and observe their behaviors (Horwitz and Christie, 2000). GenScope provides six different observational levels (i.e., molecules, chromosomes, cells, organisms, pedigrees, and populations) for genetic descriptions with their representation and manipulation means, which can be flexibly devised or restrained for use depending on the particular levels of learners and activities (Horwitz, 1999; Horwitz and Christie, 2000). GenScope is an example of a specific expertise cognitive tool, as each case is run by its implicit rules. In this example, tools do not give learners any kind of correct visualizations or models so that learners themselves have to decide what and how to model or visualize phenomena with what values. The cognitive function of these tools is to bridge the space between the decisions of learners and the visual products.

Simulation tools are similar to manipulative tools in observing object behaviors, but they do not allow learners to manipulate objects. MicroObservatory, for example, is specifically designed for astronomical observations of the sky, which provides a network of five automated telescopes controlled over the Internet from which learners can take images for their own scientific observations (Sadler et al., 2000). MicroObservatory was set-up for educational purposes to simulate a real-world scientific tool.

Tools that traverse boundaries

The tools described above cannot be said to belong to their boxes at all times as illustrated in Table 2. Some tools encompass multiple levels of executive control and others include some functions outside of the defined boundaries. Some tools are even designed to allow multiple representations with various levels of specificity in order to provide diverse channels of understanding (Kozma, 2000b). A few award-winning multimedia programs that are primarily structured for exploratory lessons also employ cognitive tools as part of their activities within a lesson. Exploring the Nardoo, a structured multimedia environment wherein learners work within the specific content area of ecology, uses metaphors of real-world problems and realistic settings that involve cognitive tools (e.g., a note-taking facility, genre templates, and interactive simulators) for problem solving activities (Harper et al., 2000). Bio-World, SICUN, and RadTutor provide simulated environments for medical informatics, giving students opportunities to practice their problem-solving and hypothesis-testing skills using provided cognitive tools (i.e., evidence palette, online library, and online simulations) within the context of managing clinical cases (Lajoie and Azevedo, 2000).

As the *lowest* level of providing specific functions to perform tasks, programming languages require a heavy cognitive load for most learners to understand them before they can focus sufficiently on other authentic activities or tasks. Logo was invented to provide an easier programming language for children. Logo evolved into StarLogo, and it is now scaffolded with a more visual interface (Jonassen and Reeves, 1996; Resnick, 1996). With the scaffolded visual interface, StarLogo shares some similar characteristics with authoring tools.

In some cases, programming languages are not only the means, but the ends for learning. Recognizing the problem of novice engineers' over reliance on the finished product to learn the process, INCENSE was created as a scaffolded learning interface that helps novice students to learn the process of software engineering (Akhras and Self, 2000). Some researchers have employed expert system shells with IF-THEN rules in classrooms, requiring learners to actually build production rule expert systems recognizing that people who design expert systems gain considerable knowledge about expert performance (Jonassen and Carr, 2000). With its scaffolded learning interface in the area of programming, INCENSE has aspects of manipulative tools we categorized as domain *specific* cognitive tools.

Programs that provide *general* expertise with *high* executive functions mostly expect users to perform better by using them, but ultimately to gain "cognitive residue" related to certain cognitive skills, such as inquiry skills and meta-cognitive skills. Writing Partner

(Salomon, 1993a, b, c) guides students' writing process, but the purpose is not for learners to use this program for every writing task, but to master a way to think about writing by working with this program. STAR.Legacy (Schwartz et al., 2000) and SCI-WISE (White et al., 2000) are also structured environments that teachers may use for different content to help students master the process of inquiry as their meta-level expertise. These kinds of computer programs have been introduced as cognitive tools. However, the main purpose of these programs appears to be the learning of meta-level skills, and the purpose of using them for cognitive activities is a secondary concern.

Programs providing more *specific* levels of expertise with *high* executive functions can include intelligent agents and expert systems. One such program is a children's programming environment called KidSim that enables learners to program behaviors of objects not by writing code as in programming languages, but by moving objects on the screen. The intelligent agent underlying KidSim remembers and recreates the movements (Smith et al., 1997). In many cases, these programs provide some flexibility for learners to be creative, but variations in activities are relatively limited. Some researchers identify these types of programs as cognitive tools because they unburden the cognitive load of learners. However, we put them outside of the boundary of cognitive tools because the primary judgments and decisions are not usually made by the learners.

The more control the computer has over learners' behavior, the less cognitive flexibility it affords. The programs we consider having *higher* executive functions interpret learner responses and behaviors and make decisions for learners, or provide predetermined content to learners with no particular order. The general production wizards found in productivity tools or authoring tools guide users through the process of producing something in a standard way by simply filling in templates or responding to a series of questions. This provides an easy way to produce something quickly, but this is not the way that learning should occur. Intelligent tutoring systems diagnose students' knowledge structures, skills, and/or styles to decide what they need to do next and adapt instruction accordingly (Shute and Psotka, 1996). Intelligent tutoring systems basically make dynamic decisions for learners – often very good ones – by intelligently behaving during their learning process (Salomon, 1990); nonetheless their purpose is fundamentally different from cognitive tools that learners employ for their learning activities. Multimedia environments present information using various forms of communication, such as text, sound, graphics, animation, and video, in one educational program (Jonassen and Reeves, 1996). Multimedia environments, such as Exploring the Nardoo (Harper et al., 2000), leave some decision-making to learners. Various information presentations using multimedia exist within the program but are open to learners' activation and sequencing until learners decide to watch, hear, and/or read them. Intelligent tutoring systems and multimedia environments are good examples of the higher executive functions as most of the decisions are made by the computer programs but heavily dependant upon some learner decisions, inputs and/or behaviors.

Computer-based tests and information presentations, on the other hand, usually exemplify computer programs with the *highest* executive functions. Computer-based tests mainly consist of multiple-choice questions, score answers to questions while or immediately after taking one, and instantly provide results when finished. In an adaptive testing, each answer is scored before the next question is selected in order to adapt the level of difficulty based on the performance (Educational Testing Service, 2005). Information presentations provide sequenced arrangements with little required learner inputs and controls. The presentations can include both verbal and pictorial information with text, sounds, and images (Mayer and Moreno, 2003). Both computer-based tests and information presentations give little or no control over the process to the learners. Some educational motion pictures, such as *Powers of Ten* (Eames and Eames, 1977), are a form of information presentations through a different medium and are very powerful in conveying the important messages about systems and connections. Taking advantage of the capabilities of computers, this particular film been modified into an interactive multimedia environment, but only allows modest learner control such as decreasing or increasing the view magnitude.

Expertise manifested in the design of activities

A tool's purpose changes depending on its use, i.e., the user's activities with the tool. The difference between the expertise of persons and that of tools is that the former can be developed (or degraded) over time whereas the latter is designed and remains the same as long as the tool designer does not make modifications. Changes in the performance of a cognitive tool happen when the partnering person changes its use, e.g., when a graphing calculator is used to display the distribution of test scores, and then used to analyze a pattern of physics experiment results.

The design of cognitive tools and activities for learners should be distinguished from that of other kinds of computers and activities. Cognitive tools are for profound thinking, similar to that required by people engaged in real problem-solving situations. We must think about these different purposes and meanings of tools in designing and using them for learning activities. Activities using cognitive tools should convey the common usage of similar tools in the world as well as the expertise of the people using those tools. The design of a tool becomes worthwhile only because of the meaningful activities it can afford (Salomon, 1993a).

Going back to the Oppenheimer's (1997) analogy of hammer and carpentry, we should not teach hammer instead of carpentry, but we cannot do carpentry without a hammer. The ways that cognitive activities are performed in the world also cannot be described without describing the roles of tools (Perkins, 1993). Many domains of experts now use computers as a part of their professional activities, varying from organizing and representing their thinking to creating actual products (Ericsson and Smith, 1991). Indeed, for scientists, the advancement of knowledge in many scientific domains is now so dependent on computers that computer modeling has become as important as theory construction and experimentation (Pagels, 1988). As computer tools increasingly change the processes and outcomes of activities in the world, tools and activities in the classroom should change to reflect the nature of real-world practices.

How learning activities are carried out in classrooms for certain topics can be very different depending upon the different levels of cognitive tools adopted. To use a cognitive tool, the teacher and/or learners usually must change or modify their learning activities. With the same topic in a subject, you could use a general cognitive tool, a generic cognitive tool, or a specific cognitive tool. To learn about genetics, learners could engage in manipulation and observation of species using Genscope. On the other hand, the teacher could design a task with microworlds that focuses on understanding underlying DNA rules to create a dynamic system. Using a multimedia authoring tool, a general level cognitive tool, may involve a completely different kind of activity, such as making a multimedia presentation about genetic mutation. The biggest difference among these activities would be their similarities to the practices of real-world experts. The more specific the tools are, the more similar the activities would be to that of experts, manifesting expertise in the world.

Some researchers have developed curriculum that incorporates the experience of real-world experts using tools. The Learning Through Collaborative Visualization (CoVis) project promotes open-ended inquiry within constructivist learning environment (Edelson et al., 1996). CoVis is based upon a technology-supported inquiry learning design framework that includes the identification of motivational context, the selection and sequencing of activities, the design of investigation tools, and the creation of process support such as scientific visualization software (Weather Visualizer and World Watcher) and other technological supports for learning (Collaboratory Notebook, Internetworking Tools) (Edelson et al., 1999). One CoVis study investigated the implementation of the Global Warming Curriculum within a 6-week period, during which middle and high school students prepared briefings for a fictitious global warming conference. The study showed that CoVis project provided learners with a coherent motivating context assuming the role of scientists, but the study also raised the issue of the large time commitment needed to implement such in-depth inquiry-based learning (Edelson et al., 1999).

The development of joint learning systems

Engelbart classified four basic ‘‘human augmentation means’’ (citied in Rheingold, 1985, p. 182): artifacts (physically designed to manipulate other things), language (as means to think and attach meanings to the world), methodology (as in method, procedures, and strategies for problem-solving activities), and training (for skills in using other means). He visualized an augmented system as a trained human being together with a set of artifacts, language, and methodology. These four classes manifest both ideas of distributed cognition and expertise in that the human is dependent on the environment (artifacts and language) (i.e., physical and symbolic distribution) and is trained to use skills (methodology and training) (i.e., development of expertise).

Joint learning system

When the computer was first introduced into education, it was viewed as a mere delivery medium of established cognition, not much different from a book or an organized shelf of books (Pea, 1993). Outside of schools, the role of computer tools has become increasingly important in highly intellectual tasks, even as a necessary means for completing tasks (Salomon et al., 1991; Pea, 1993; Salomon, 1993b). As the participation of a person with a different set of skills in a task changes the nature of an activity, computers have changed the nature of tasks in many domains (e.g., statistical analysis). Computers as cognitive tools beyond delivery media lead to fundamental changes in cognitive activities, ideally to producing higher levels of thinking (Vygotsky, 1978; Cobb et al., 1997).

The knowledge and performance that result from cognitive effort, therefore, cannot be attributed solely to a person because they are the product of joint participation among people and tools (Salomon, 1993a; Karasavvidis, 2002). The outcomes of distributed cognition include not just constructed knowledge or performance, but also resulting cognitive process and distributed structure through the joint relationship. These implicit outcomes of joint thinking become important parts of a person's cognitive development. Development of cognitive processes mediated by the affordances of the joint system produces an even stronger structure of distributed cognition (Salomon, 1993a).

Charness (1991) studied human chess expertise with a computer chess game opponent. The expertise of any given chess player, ranked as grandmaster, international master, master, expert, and so forth, appears as a stable quality of the player. The player's use of this expertise, however, depends largely on what kind of move the computer makes (which depends on the previous move of the player) and what kinds of patterns the player has encountered before; the player even discovers new patterns and strategies as he or she proceeds. The player's cognition is distributed to the computer socially (as an opponent player), symbolically (by sharing same conventions), and physically (as an object).

In learning situations, learner(s) and tools with a meaningful task form a joint system of learning. Figure 1 illustrates our suppositions on how a joint learning system performs within and outside the designed activity (task) and how its performance outside of the boundary changes over time, as its expertise develops as a system. The participants of the joint learning system (the learner(s) and the tool) come to share and develop shared language and methodology.

Growing expertise of the joint learning system

Salomon et al. (1991) regarded computers as "partners in cognition" when learners work with them during cognitive tasks. What does it mean to become a partner? Human partners bring their unique expertise to a team; partners strive to know about each other's

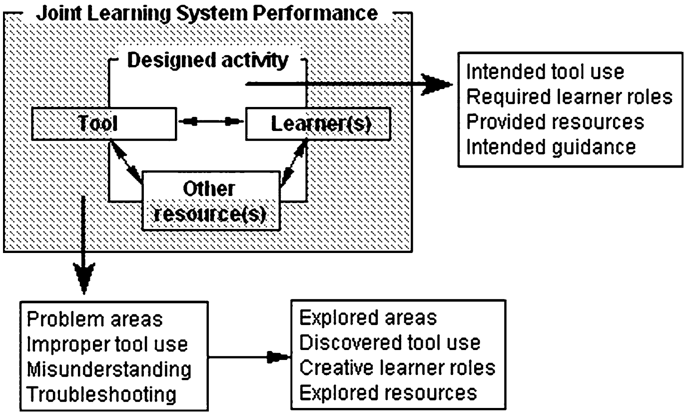

Figure 1. Joint learning system and its changes in performances.

strengths and weaknesses to build their relationship and work effectively together. Cognitive partnerships with computers take place in a similar fashion and require substantial efforts to become a strong team. When partners of distributed cognition are continually involved in activities together, the distributed system is likely to develop into a more sophisticated relationship. The sum of isolated cognitions cannot adequately represent the workings of the distributed cognition; thus the cognitive growth of an individual cannot be understood without understanding the development of joint cognitive relationships. Theories of expertise and distributed cognition shed new light on the partnerships between humans and their cognitive tools.

Once partners join a team with their expertise, they strive get to know each other to perform their tasks. Similarly, when new technology is introduced to an individual in a problem-solving situation, the person has to deal with this new relationship with technology. Learners do not automatically think productively with cognitive tools from the start. The cognitive load of a tool's interface is highly evident, making the affordances of the tool less obvious to the learner, and thus, the partnership of the joint system remains weak for some time (Pea, 1993). With a new cognitive tool, higher-level thinking may be limited as long as users struggle to make the technology itself work. Then the cognitive load devoted to the tool use per se reduces as individuals grow accustomed to its use, and they are able to engage in higher order thinking. In Figure 1, the performance of joint learning system outside of the designed activity is first focused more on problem areas, such as improper tool use, misunderstanding and troubleshooting.

When individuals see the value of using tools in their cognitive activities, they are willing to engage in the process of learning the tools so that they can adapt them for their activities (Perkins and Grotzer, 1997; Wertsch, 1998). Expertise of the learner and the joint system grow with each other in a synergistic way. The learners' growing expertise in the domain and increasing familiarity with the tool (i.e., knowledge structure, problem-solving strategies, and automaticity) are important if the learner is able to take advantage of the expertise of the tool. Likewise, the performed expertise of the tool stimulates the development of the learner's cognition, resulting in stronger joint expertise. Learning to use a tool, therefore, is not a process that happens only at the beginning but is rather an ongoing process; learners discover more affordances of tools and even refine their own abilities as they master the tools and develop more effective distributed relationships. In other words, the interface of the cognitive tool becomes less visible to the learners, the affordances of it more obvious, and the partnership of the two stronger. In this way, the new tool, the existing environments, and the person together contribute to the distributed cognition in activities (Pea, 1993). Eventually, the joint system synergy enables the learner to understand the world with more profound meanings (Falbel, 1991; Salomon and Almog, 1998).

The development of distributed cognition might go through a major transitioning phase when confronting novel situations. When a unique problem-solving situation is thrown into a distributed cognition structure, individuals again have to find novel uses of tools and adjust the structure and workings of distributed cognition. At the same time, the growth in the joint system changes the way activities are carried out. The structure of joint expertise transforms as elements (i.e., knowledge, function, and representation) are modified or take new forms, altering the way they interact with each other. The strengths and weaknesses of both the learner and the tool become clearer by finding the roles of each in relation to the activities (Pea, 1993). The focus of their activities outside of the boundary (Figure 1) then becomes on the explored areas, such as discovered tool use, creative learner roles, and explored resources. Cognitive tools should be designed to be flexible and open to this growth, providing learners with opportunities to be mindful and creative in their activities (Salomon et al., 1991; Jonassen and Reeves, 1996).

Researching the action of the joint learning system and extended unit of analysis

In the perspective of distributed cognition, environments and their sub-components are seen as integral parts of human cognitive activities. From this view, individual ability and distributed structure should be considered together to understand cognitive activities (Nickerson, 1993; Salomon, 1993a). It has been recognized that a distributed system of cognition cannot be understood by examining its parts in isolation, and thus recent research in cognition moves away from just seeing an individual as a unit of analysis to viewing a system of individuals and the environment in action as a legitimate unit of analysis (e.g., Lave, 1988; Brown et al., 1993; Pea, 1993; Perkins, 1993; Hutchins, 1995; Wertsch, 1998).

For the research on cognitive tools, the unit of analysis should be learners together with computers, in order to encompass their intellectual partnerships as they are forming and evolving. The extended unit of analysis includes a cognitive tool as an inseparable entity for learner capabilities; at the same time, each tool should be considered as having its own contributing qualities (Salomon, 1993a). We believe that the distributed cognition plus expertise view suggests a way to look at two kinds of completely different subjects (i.e., learners and tools) as partners and interacting constituents of a compound system. Detailed concepts of these theories (e.g., elements of expertise structure: knowledge, function and representation) becomes important constructs for understanding the qualities of each. The performance of the tool, therefore, should be given a similar amount of attention given to that of learners.

Understanding the complex nature of a distributed cognitive system requires studying it in action during the time when the interaction is actually happening – not before or after (Wertsch, 1991; Pea, 1993). The learner or the tool alone without any interaction is no longer a distributed system even though there is a potential relationship between the two. Just as various kinds of designed artifacts have intended uses for certain types of activities, educational settings usually have activities that are designed for potential relationships among interacting units to promote opportunities to learn. The emergent characteristics of a learner, however, cannot be understood without taking into account his or her relationships with certain activities and specific tools in a particular time.

Distributed cognition can be seen from both analytic and systemic views. From an analytic view, the distribution is a set of cognitive functions coming together to perform a task; from a systemic view, the distribution is a natural status of a cognitive task performance (Nickerson, 1993). The structure of cognitive distribution can be designed and studied to facilitate cognitive activities (analytically) as well as be observed and studied as a phenomenon (systemically) (Pea, 1993; Bell and Winn, 2000). Whether by design or by nature, the structure of distributed cognition is not a static condition, but dynamically embedded in human activities; the structure evolves and changes over time, thus holding both intentional and natural characteristics (Pea, 1993; Perkins, 1993).

Implications for research and practice of cognitive tools

The term, "cognitive tool" is used with different conceptual meanings in other fields of knowledge, such as the studies of language as a cognitive tool. In the field of Instructional Technology, cognitive tools have been viewed too simplistically as tangible objects that learners use for their learning. Rethinking cognitive tools, therefore, is important if we are to advance the meaning of the term for design, development, research and practice beyond its abstract conception (Table 3). In this paper, we have recommended the theories of distributed cognition and expertise to advance ideas and research about cognitive tools. These two theories together help us examine the expertise of every participant of an activity, including a cognitive tool, which contributes to the distributed cognition in performing the task. Using these two theories as lenses, we re-conceptualized cognitive tools as technologies that are designed to bring their expertise to the performance and, in result, with which learners interact and think in knowledge construction. Several principles for the research and development of cognitive tools can be recapitulated from the discussions above.

Tool design: differentiate the capabilities of the tool from those of the human

Some argue that we need to be aware of the potential losses in our intellectual abilities when using any new intellectual tool (Egan, 1998). In terms of cognitive tools for learning, we should think about these effects even earlier, when we design them. As the cognitive tool participates in the cognitive activity of learners, it alters the way they think

Table 3. The concept, design, application, and research of cognitive tools

	Concept	Design	Application	Research
Cognitive tool	Technologies that learners interact and think with in knowledge construction, designed to bring their expertise to the performance	General tool Generic tool Specific tool		
Activity		Designed to reflect expertise of the world		
Joint learning system			Joint learning system in action: learners-tool-activity	Analytic approach to the distribution
Joint learning system development			Growing expertise of joint learning system	Systemic approach to the evolution of expertise

and act. Understanding how the tool may enable and constrain the possible activities within the learning environment should help us design tools that actually empower learners in their thinking (Kozma, 2000b). The design of tools should be centered on the things that computers can do better than humans without taking over the most important cognitive tasks of learners (Dreyfus and Dreyfus, 1986; Norman, 1993).

Initially, computer tools were developed and researched specifically to capture the expertise of experts within the field of artificial intelligence or to be used in the classrooms for teaching school subjects. The major mistake of both traditions was their focus on the design of machines that resemble what we already have in our environment (i.e., experts and teachers). The design of cognitive tools for learning should be founded on the complete understanding of appropriate learning theories and the unique processing capabilities of computers (Kozma, 2000b). To this end, the first thing we need to remember (in relation to the theory of distributed cognition) is that tools designed to extend cognitive capabilities of learners should reflect what it means to have a distribution of cognition. Many computer tools are competitively developed nowadays for similar uses, pitching any special features that differentiate them from their competitors. A tool's distinctive qualities from other tools, however, are not as important as its affordances that are distinctive from humans for contributing to the performance of tasks.

Activity design: regard cognitive tools as part of human expertise and situate them in appropriate activities

Today's real-world cognitive tools are part of the capabilities of experts. Hence, we should think about the design of cognitive tools for learning in relation to the theory of expertise. Tools in general are integral parts of human activities, and the capacity to use tools is critical in judging our competence levels in many domains (Cobb et al., 1997; Wertsch, 1998). Computerized tools nowadays are increasingly critical parts of our cognitive activities, and in many fields, expertise can not be accounted for without understanding experts' use of their tools. The design of cognitive tools should allow learners not only to use the tools to learn specific content for planned lessons, but also to use them in other relevant problem solving situations in ways similar to how experts use their tools for various problems. We should not attempt to assess the knowledge of learners without their cognitive tools any more than we would assess the expertise of scientists without their tools.

Computers as cognitive tools are essential for learners to be active in contemporary constructivist learning environments. Ideally, the application of cognitive tools for learning in schools or other educational contexts (e.g., online) should resemble the use of cognitive tools in the world. This means that activities in the world, including their processes and products, are replicated in the classroom or in the online learning environment. Cognitive tools thus should be adopted to transform the way learners interact in the classroom from the passivity of lectures to doing authentic tasks similar to the ones pursued in the world (Herrington et al., 2003). The activities should be planned to afford learners' opportunities to design their own solutions to problems, taking advantage of the capabilities of technology (Kozma, 2000b).

Research and practice for the partnership: assess learners with their tools

By perceiving a tool as a partner of cognition working together towards an activity such as solving a problem or accomplishing a task, the boundaries between cognitive process and the outcomes of cognitive process become fuzzy. The skills and strategies that learners gain through the partnership (the effect "of") become learners' capabilities to perform better during the partnership (effect "with"). Thus, learning can only be assessed appropriately by examining a learner's performance with a tool. Some disappointment concerning learning performance derived from the adoption of cognitive tools comes from the measurement of the learner's cognitive outcomes in a completely different situation, i.e., without the tool (Salomon and Almog, 1998).

Research on learning with cognitive tools, therefore, should account for the various aspects of learning situations that we have discussed. The researchers should be able to scrutinize the effects "with" a cognitive tool and the resulting effects "of" it on the learners, which ultimately influence the effects "with" the tool when learners work with it again. These evolving effects and various transitions can only be understood when we observe learners working with the tool over a longer period time so that they actually build their relationship with the tool. The proposed integrated framework for cognitive tools provides ways to examine computer tools with respect to what affordances tools should have in what areas of expertise in what levels with what kind of structures, and what roles we expect learners to play in the structure of distributed cognition. Various alternative research approaches should be adopted in order to capture this complex cognitive relationship within the distributed system (Kelly, 2003). As important bases of our theory, practice, and research, the understanding of this relationship should contribute to pedagogical and instructional design knowledge in education (Kozma, 2000b).

Research and practice for growth: study learner initiation and the development of the distributed cognitive relationship

The mastering of nature and the mastering of behavior are mutually linked, just as man's alteration of nature alters man's own nature (Vygotsky, 1978, p. 55). "Ms. S., I don't have a HyperCard mind," blurted a child during the research conducted by Brown et al. (1993). Despite high expectations, the researchers found that children were not able to exploit many of the complex features of HyperCard successfully (Brown et al., 1993); the affordances of the tool were provided, but never used. It is important to provide learners many opportunities to initiate distributed relationships with tools and learn how to master and work with tools in cognitive activities that require the expertise of tools. They also need to learn how to design the structure of distribution by exploiting the critical expertise of other learners and certain tools among various resources. The development of expertise with cognitive tools in collaboration with others is one of the most important aspects of human activities and performances outside of school, and so should it be inside school (Pea, 1993).

To make a successful transition to the new distribution relationship, teachers and instructional designers should allow more time for the skills and knowledge development of individuals with gradually fading degrees of external support (Glaser, 1996; Salomon, 1993a). Learning activities should be focused on mastering various features of the tool itself while maintaining the relevance of the real context of problem solving situations. Teaching the tool without a meaningful context is detrimental to advanced learning. As learners work with the tools they should become confident in assessing the problem situations, developing their own strategies, and monitoring their progress (Kozma, 2000b). Once they make this transition and gain expertise with the tool, they will recognize when to rely on the tool and when not to (Pea, 1993; Salomon, Salomon, 1993a). Evolving expertise reveals more capacities and functions of the tool in the performance of tasks, and this continuous reciprocal process that happens during learning activities makes expertise grow even more (Salomon, 1993a).

Final thoughts on cognitive tools

Researchers often make analogies to physical tools to explain cognitive tools. However, the analogy does not last once researchers get into the substantive conversations about cognitive tools. In the earlier research literature, intelligent agents, which we classified as outside the margins of cognitive tools in Table 1, were perceived as cognitive tools by becoming advisors or by hiding complex rules behind the computer and letting users do the easy hands-on tasks. We believe these tools have different purposes from cognitive tools. Consider a physical tool, say a tennis racket, specifically for the effects "with" and "of" its use. A tennis racket extends human capabilities (e.g., increasing probabilities of reaching the ball and hitting it to a certain direction) by virtue of its involvement in the game's activities together with the person (effects "with"). The role of a coach, by contrast, is giving advice, e.g., a coach's revealing of rules and helpful tips may help the player master the game. The physical residue of using the racket (effects "of") could be a stronger arm and healthier body, which transfers to other kinds of athletic activities, whereas the cognitive residue of coaching could be more knowledge about how to grip and swing the racket. We do not try to examine how well people play tennis without giving them a racket, expecting them to play as good as they could with it (Salomon et al., 1991).

Although the role of cognitive tools is similar to that of physical tools, which is to provide an extension of our abilities, there is an important fundamental difference. The resulting effect of using real cognitive tools should be the better use of the tool itself for cognitive activities as well as substantial cognitive growth that transfers to other kinds of cognitive activities. The essential nature of a cognitive tool cannot help someone learn without the appropriate use of a tool, but the nature of a cognitive tools differ from that of traditional tools in that as expertise grows we can adapt them for new creative activities. No amount of practice and coaching will enable someone to use a tennis racket to play golf, but practice and guidance with using cognitive tools may yield to innovative ways of thinking and problem solving that educators have not even begun to imagine.

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