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Practices of distributed intelligence and designs for education

Roy D. Pea

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Distributed cognitions

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- Münsterberg, H. (1914). *Psychology: General and applied*. New York: Appleton.
- Palincsar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering and monitoring activities. *Cognition and Instruction, 1*, 117-75.
- Rubin, J. Z., Provezano, F. J., & Luria, Z. (1974). The eye of the beholder: Parents' view on sex of newborns. *American Journal of Orthopsychiatry, 44*, 512-19.
- Scardamalia, M., & Bereiter, C. (1985). Fostering the development of self-regulation in children's knowledge processing. In S. F. Shipman, J. W. Segal, & R. Glaser (Eds.), *Thinking and learning skills: Research and open questions* (pp. 65-80). Hillsdale, NJ: Erlbaum.
- Schwartz, T. (1978). The size and shape of culture. In F. Barth (Ed.), *Scale and social organization* (pp. 215-52). Oslo: Universitetsforlaget.
- (1990). The structure of national cultures. In P. Funke (Ed.), *Understanding the USA* (pp. 110-49). Tübingen: Gunter Narr.
- Shorter, E. (1985). *Bedside manners: The troubled history of doctors and patients*. New York: Simon & Schuster.
- Stocking, G. (1968). *Race, culture, and evolution*. New York: Free Press.
- Toulmin, S. (1981). Toward reintegration: An agenda for psychology's second century. In R. A. Kasschau & C. N. Coter (Eds.), *Psychology's second century: enduring issues* (pp. 264-86). New York: Praeger.
- Valsiner, J. (1988). *Developmental psychology in the Soviet Union*. Bloomington: Indiana University Press.
- Vygotsky, L. S. (1929). The problem of the cultural development of the child, II. *Journal of Genetic Psychology, 36*, 415-34.
- (1960). *The development of higher psychological functions (in Russian)*. Moscow: Izdael'stov Akademii Pedagogicheskikh Nauk.
- (1978). *Mind in society*. Cambridge, MA: Harvard University Press.
- (1987). *Thinking and speech*. New York: Plenum. (Originally published 1934.)
- Wertsch, J. (1985). *The social formation of mind*. Cambridge, MA: Harvard University Press.
- White, L. (1942). On the use of tools by primates. *Journal of Comparative Psychology, 34*, 369-74.
- (1959). The concept of culture. *American Anthropologist, 61*, 227-51.
- Wundt, W. (1921). *Elements of folk psychology*. London: Allen & Unwin.

2 Practices of distributed intelligence and designs for education

Roy D. Pea

Introduction

Widespread conceptions of learning and reasoning invoke "intelligence" largely as a property of the minds of individuals. This belief is prevalent in educational settings, which are concerned largely with solitary intelligence. Intelligence, they say, is what testing firms test and, increasingly commonly, what schools need to be held more accountable to measuring and improving.

Problems lurk in these assumptions. Anyone who has closely observed the practices of cognition is struck by the fact that the "mind" rarely works alone. The intelligences revealed through these practices are distributed – across minds, persons, and the symbolic and physical environments, both natural and artificial. Gregory Bateson remarked that memory is half in the head and half in the world. In this chapter, I will first lay out the central ideas of the distributed-intelligence framework and then provide a background to its development, before closing with considerations of some implications for education. How we think about these relations may change what we

Portions of this chapter were originally slated to appear in a book edited by David Perkins and Becky Simmons of Harvard University's Educational Technology Center. Plans for that book subsequently foundered, and portions of my essay (Pea, 1988) appear here as a necessary pretext to subsequent work. Previous papers on this theme were first presented in April 1988 to the First Annual Cognition and Education Workshop, Bolt, Beranek and Newman, Inc., Cambridge, Massachusetts, and at the 1988 Cognitive Science Society Meetings. Related work was described at the 1989 Social Science Research Council Conference on Social Aspects of Computing (in which Gavriel Salomon and David Perkins participated) and in the 1990 American Educational Research Association Symposium on Distributed Intelligence, which led to the plan for this book. I am indebted to Christina Allen for provocative discussions of distributed intelligence, especially concerning design and the roles of human desires.

do with technologies in education – not only computational media, but also social technologies for supporting learning such as guided participation or peer collaboration and learning/teaching materials more broadly. While providing few answers, I hope to provoke new questions and inquiries, for distributed intelligence is not a theory of mind, or culture, or design, or symbol systems and their impact on human thought so much as it is a heuristic framework for raising and addressing theoretical and empirical questions about these and other topics.

While the relevance of these concepts is not restricted to learning in mathematics, science, and technology, I will often use examples and issues in these fields for making my points, since the roles for distributed intelligence perhaps stand out in greater relief in these domains than in other areas of learning, education, and work.

The nature and concepts of distributed intelligence

Knowledge is commonly socially constructed, through collaborative efforts toward shared objectives or by dialogues and challenges brought about by differences in persons' perspectives. Intelligence may also be distributed for use in designed artifacts as diverse as physical tools, representations such as diagrams, and computer–user interfaces to complex tasks. In these cases, intelligence is often distributed by off-loading what could be elaborate and error-prone mental reasoning processes as action constraints of either the physical or symbolic environments.

On close inspection, the environments in which humans live are thick with invented artifacts that are in constant use for structuring activity, for saving mental work, or for avoiding error, and they are adapted creatively almost without notice. These ubiquitous mediating structures that both organize and constrain activity include not only designed objects such as tools, control instruments, and symbolic representations like graphs, diagrams, text, plans, and pictures, but people in social relations, as well as features and landmarks in the physical environment. Imagine the absence of the following resources and the detrimental effects of that absence on the activities to which they may contribute intelligence: keyboard letters, labels on instrument controls, everyday notes, well-placed questions, the use of space

to organize piles of materials on a desktop, the emergent text in a written composition one is constructing. These everyday cases show the active and evolving structuring of the material and social environments to make them a repository of action mediators. Unlike other species, such as Simon's (1981) ant on the beach, whose complexity of behavior is determined more by the shape of its environment than by its mental contents, humans have desires that lead them to recraft their environments to carry out aspects of reasoning, to make reminders for action, and to get help from others. When talking about distributed intelligence, then, I mean that resources in the world are used, or come together in use, to shape and direct possible activity emerging from desire. This is not to claim, of course, that *all* intelligence is or can be so distributed, but that there is a constitutive trend in this direction to be found in cultural history, ontogenesis, and the microgenesis of activity.

The distributed-intelligence orientation that I describe, which takes these observations as central data about cognition, stands in sharp contrast to the common focus on "intelligence" as an attribute of individuals, carried primarily in internal transformations of mental representations of symbols for goals, objects, and relations. Theories of education building on these notions are concerned largely with solitary intelligence, decontextualized from its uses in activities beyond the educational. Analyses of our designs for such distributions may be more revealing for understanding cognition than are studies of the formation and transformation of mental representations that have come to define cognitive science and educational studies based on this field.

Some key interrelated concepts I will use require clarification. These include "intelligence," "activity," "distributed," "means–end adaptivity," "affordances," and "desire."

Intelligence as distributed and manifest in activity

The primary sense of distributed intelligence arises from thinking of people in action.¹ We begin with activity, expressing

¹ I take the work of Leont'ev (1978a, b) on activity theory as arguing forcibly for the centrality of people-in-action, activity systems, as units of analysis for deepening our understanding of thinking. On related philosophical grounds, Wartofsky's (1979,

action rather than a state of being. In such activity, we see the *configuring* of distributed intelligence. Activity is enabled by intelligence, but not only intelligence contributed by the individual agent. When I say that intelligence is distributed, I mean that the resources that shape and enable activity are distributed in configuration across people, environments, and situations. In other words, intelligence is accomplished rather than possessed. The intentionality of activity may originate with the agent's desires or the hopes of a designer wishing to bring the affordances of a new artifact into the configuration of another agent's activity. While it is people who are in activity, artifacts commonly provide resources for its guidance and augmentation. The design of artifacts, both historically by others and opportunistically in the midst of one's activity, can advance that activity by shaping what are possible and what are necessary elements of that activity.

What is meant by *intelligence* as distributed? I use the phrase "distributed intelligence" rather than "distributed cognition," because *people*, not designed objects,² "do" cognition. Yet I want to capture the important fact that intelligence, which comes to life during human activities, may be crafted. There are both social and material dimensions of this distribution. The social distribution of intelligence comes from its construction in activities such as the guided participation in joint action common in parent-child interaction or apprenticeship, or through people's collaborative efforts to achieve shared aims. The material distribution of intelligence originates in the situated invention of uses for aspects of the environment or the exploitation of the affordances of designed artifacts, either of which may contribute to supporting the achievement of an activity's purpose.

Activity is achieved in means-end adaptations. These adaptations may be more or less successful. The focus in thinking about distributed intelligence is not on intelligence as an abstract property or quantity residing in minds, organizations, or objects. In its primary sense here, intelligence is manifest in activity that connects means and ends through achievements. I also do not mean "intelligent" in

1983) historical epistemology also highlights external action, or praxis, as the focus of understanding for psychological development.

² I leave designed objects such as "artificially intelligent" computer software aside for the moment, concentrating on noncomputational objects. Whether computer programs engage in cognition is not a topic of this chapter.

the generic folk value sense, so I reject "distributed foolishness" or "stupidity" as antonyms of "distributed intelligence." These are values at the evaluation level of the action itself (e.g., "Bank robbing is a stupid and not an intelligent act") or in terms of norms regarding, for example, the efficiency of means-end adaptivity, as in "Using a rock to hammer a nail is stupid; using a hammer is more intelligent."

Affordances

How do tools serve as artifacts of distributed intelligence, carrying along with them new opportunities for contributing to activity, as defined by a community of users of such tools? I begin this inquiry by noting the focal relevance of works by Vygotsky, Simon, and Gibson. Each of these theorists considered questions about the distribution of intelligence between the world and the mind to be fundamental. Vygotsky (1978) placed great emphasis on the ways in which the character of social interactions and externally mediated action makes explicit certain processes that come to be internalized in the private thought of the individual. In Simon's (1981) seminal work, *The Sciences of the Artificial*, he questions whether what we often consider the complexity of some act of thought may have more to do with the complexity of the environment in which action takes place than with the intrinsic mental complexity of the activity. In pointing to the mind-environment interface, Simon suggests looking at problem solving as distributed between mind and the mediational structures that the world offers. In Gibson's (1979, 1982) work on the ecology of perception, the notion of "affordances" of objects that link perception and action is central. "Affordance" refers to the perceived and actual properties of a thing, primarily those functional properties that determine just how the thing could possibly be used. Less technically, a doorknob *is for* turning, a wagon handle *is for* pulling.

Research examining the concept of affordances is critical if we are to build a science of distributed intelligence and a more flexible design orientation to the practices of education. For many of the hoped-for goals of education, we presuppose the success of the social constructability of affordances – that one can get a learner to attend to

the pertinent properties of the environment, or the designed object, or the inscriptional notations, such that the learner can join in to contribute to distributed intelligence in activity. For a given activity, and the various means for its achievement, there can be considerable variation in the ease with which one can show a learner how to exploit those means to form a system of distributed intelligence for achieving that task. This will vary with the learner's background experiences, the obviousness of the mapping between the learner's desire or goal, and the assimilation of the artifact as means toward it. Such a meeting of intentionality and artifact in activity is thus not simply the direct perceptual pickup of the affordance structure of the object or notation, as radical Gibsonians would have it. Culture and context contribute to its achievement.

Norman (1988) has done a great service both to the field of design and to psychology in developing Gibson's insights on affordances (which largely underplayed the cultural factors involved in learning to use humanly designed objects) into what he calls a "psychology of everyday things." Norman offers many examples – microwave ovens, videocassette recorders, car instrument panels, slide projectors, even water faucets – to show how affordances of objects deeply and often unnecessarily restrict their *accessibility* to the ordinary human. The point is that better design of artifacts would make it easier to accomplish certain functions. One would like to be able just to look and see what to do, and then do it, without instruction, without manuals, without complex deductions. Such "efficiency" of action is also a tacit objective of cognition in practice. Everyone can imagine a few examples of powerful representational tools that are not obvious in function (e.g., the static x - y coordinate graph, static ray diagrams in optics) and make apparent that what Norman calls the "psychopathology of everyday things" may carry over only too well to an account of the psychopathology of instructional artifacts and representations in mathematics and science.

Lave (1988) offers many examples of "smart tools" that we may point to as illustrations of the everyday presence of such distributed intelligence. She describes how measurement activities are often achieved with special-purpose "stashes" of numerical information embodied in measuring instruments. Examples include such invisible cases as the dime-store thermometer, yardstick, auto speedometer,

and home thermostat. Many of these objects have become "mythic," as Roland Barthes (1972) uses this term, in that they have become so deeply a part of our consciousness that we do not notice them. Turned from history into nature, they are invisible, un-"remarkable" aspects of our experiential world. A large number of such "smart objects," especially for measurement and for calculation, but also as reminding devices, are appearing. They are becoming especially prevalent as microprocessors enter the fabric of everyday activities by the tens of millions. Finding marketable niches for such efficiency, many of these devices reify common problem formats and automate solution-finding procedures. Examples include jogger pulse meters, automatic street locators, currency exchange calculators, world-time clocks, and weight-loss calculators.

These tools literally carry intelligence *in* them, in that they represent some individual's or some community's decision that the means thus offered should be reified, made stable, as a quasi-permanent form, for use by others. In terms of cultural history, these tools and the practices of the user community that accompany them are major carriers of patterns of previous reasoning. They may contribute to patterns of distributed intelligence configured in activity. They may now be used by a new generation with little or no awareness of the struggle that went into defining them and to adapting their characteristics to the tasks for which they were created. The inventions of Leibniz's calculus and Descartes's coordinate graphs were startling achievements; today they are routine content for high school mathematics. But as such tools become invisible, it becomes harder to see them as bearing intelligence; instead, we see the intelligence "residing" in the individual mind using the tools. This encapsulation of distributed intelligence, manifest in such human activities as measuring or computing, may arise because we are extraordinarily efficient agents, always trying to make what we have learned works usable again and again. We deploy effort-saving strategies in recognition of their cognitive economy and diminished opportunity for error (Kus-terer, 1978; Scribner, 1986).

The individual still has a primacy in activity, of course. But the distributed-intelligence framework sees a much more substantial haze around the boundary of the person and shines the light of attention on the more invisible intelligence in the artifactual, physical,

symbolic, and social surrounds, as brought into relief in the configurations of distributed intelligence by which activity is achieved.

To sum up, knowledge is often carried in artifacts as diverse as physical tools and notational systems such as algebraic equations. This knowledge may come to be exploited in activity by a new learner through a variety of genetic paths: through observations of use by other humans and attempts to imitate it, through playful discovery of its affordances in solitary activity, and through guided participation in its use by more knowledgeable others. And the affordances of such artifacts may be more or less difficult to convey to novice users of these artifacts in the activities to which they contribute distributed intelligence.

Desires

Our last major concept is “desire.” What initiates activities and designs of distributed intelligence? I find it useful to begin with Norman’s (1988) approximate model of the structure of activity. His account of seven stages of action proceeds through four stages of execution – forming a goal, forming an intention, specifying an action-sequence plan, and executing an action, and three stages of evaluation – perceiving the world state after the action, interpreting the world state, and evaluating an outcome of action in relation to the goal. Since I believe that the concept of “goal” common in cognitive science presupposes commitment to greater articulateness and mental representation than the diffusely specified *desires* that often lead to action,³ it will be important to develop some basic account of desires in order to think about the shapes of distributed intelligent activity that emerge for people.

How do people’s *desires* for a particular situation shape both their interpretation and their use of resources for activity? Human use of distributed intelligence in the designed environment to achieve activity goes far beyond either situational determinism or a decoding

³ Agre (in press), Suchman (1987), and Winograd and Flores (1987) have provided compelling arguments on this point, rooted in phenomenological works by Heidegger, Husserl, and Schutz. Their arguments on the primacy of situated action and the derivative nature of mental representation also rest on a shift of attention toward person-acting-in-setting-with-others-and-artifacts-with-cultural-histories as the to-be-explained rather than individual knowledge.

of the intentions behind the design of objects. While one who is using a hammer to strike a nail is, in the achievement of that activity, in an important sense collaborating with its designer, there is more to it than this. The process also involves the interpretation of resources and relationships for creative and novel activity (Schön, 1983). Resources of the world offer potential relationships, constrained by their affordances, that may not at all be mentally represented prior to a situational perception of their meaning. Their functional roles as components of a configuration of distributed intelligence may arise only in the course of desire-driven initiatives by an actor. This observation is profoundly true for designers, who are continually creating new objects and environments, interpreting their meaning, and revising their designs accordingly (Allen, 1988). Intelligence is contributed in each moment by the ways in which people interpret the things they are experiencing. We need to understand more fully the genesis of human desires, because people create, invent, and innovate as they create or act in designs for distributed intelligence. They do not simply act in habitual, static ways. The interpretation, relevance, and meaning of resources available for activity are shaped by the desires with which people come to situations.

Some basic distinctions are valuable for beginning to think through a useful taxonomy of desires. We can identify a small set of basic desires, not intended to be exhaustive, each of which constitutes a kind of experiential “moment” that a person brings to a situation for achieving activity:

1. With a *task* desire, one has a clear goal and intention, and the need is to specify an action with a particular means. If I am freezing in a cabin, my task desire for warmth may make the affordance of a chair for burning much more salient than its affordance for sitting. If my task desire were different, different properties of the chair would matter.
2. With a *mapping* desire, one falls short of mapping the achievement of projected activity back into the specific action to be taken with an available means. I know this tool may be used to achieve the activity, but I am uncertain of how the distributed-intelligence resources need to come together in design. In Norman’s terms, this is a gap to be closed from intention to specification of action. I have available an outline processor instead of a typewriter for writing – my

task of writing and tool are known, but now the desire is to find the ways in which this outline processor is useful for the writing task. To close this gap between desire and action may require reflective cognition, as suggested in accounts of the breakdown of "concern-full action" (Winograd & Flores, 1987).

3. With a *circumstantial* desire, one has no specific goal or intention in approaching the situation. Instead, the desire arises opportunistically in response to one's noticing properties of the situation that emerge during action. A rubber band becomes a musical instrument; a steering wheel emerges as a percussion device for the driver listening to a song. For circumstantial desire, the role of play, of exploration of potential relations into which the object can enter, cannot be underemphasized.
4. With a *habitual* desire, one merely repeats a familiar course of action incorporating the distributed-intelligence resources of the world or other persons into one's activity. Winograd and Flores (1987, p. 32) follow Heidegger in calling such unreflective, action-embedded knowledge "ready-to-hand." The blind man tapping his cane on the pavement treats it as an extension of self; it becomes invisible in its properties as means, since it is so well integrated in activity.⁴ The seven stages of action are cycled with minimal notice.

In these examples, we can see creativity emerging from situated interpretations of resources in the environment based on desires. Creativity often consists of novel interpretations in activity of desire-situation resource pairs. While more kinds of desire surely exist than the ones described,⁵ we can see the importance of the concept by noting how designs for distributed intelligence are reliant upon the specific desires in an activity.

Beginnings

How did this view of distributed intelligence arise? I can explain what it seeks to account for in terms of the paths that led to its

⁴ An example often used by Wittgenstein and Merleau-Ponty, and later by Bateson (1972).

⁵ For example, Ford and Nichols (1987) define a broad variety of human goals, including goals directed toward transactional accomplishments such as those of safety, sex and reproduction, self-esteem, establishing social relationships, and hunger satisfaction, and what they describe as internally oriented goals such as experiencing a sunset, having fun, feeling joy, avoiding stress, and spirituality.

development. As a developmental psychologist in the early 1980s with a long-term interest in the social foundations of cognitive growth, I became very intrigued with the increasingly prevalent use of technologies in society, including the widely hyped developments in artificial intelligence systems of the time. What consequences would this have for rethinking human development, learning, and educational goals and practice? I developed a cultural-historical perspective, influenced by the works of Vygotsky, Luria, and Cole and rooted in the theories of Vico, Hegel, Marx, and Engels, for addressing these questions. Cole and Engeström (Chapter 1, this volume) provide some historical context for this work, so I will not do so here. A fundamental aspect of this perspective is a view of human nature that, while acknowledging biological and environmental contributions, emphasizes that humankind is "reshaped through a dialectic of reciprocal influences: Our productive activities change the world, thereby changing the ways in which the world can change us. By shaping nature and how our interactions with it are mediated, we change ourselves" (Pea, 1985a, p. 169). Just as the use of physical machinery in farm labor came to mediate human interaction with nature in increasingly different ways, so too do computer technologies mediate human interactions with nature, information, and other persons in distinctly different ways. This argument is an extension of Vygotsky's (1930/1978) arguments in "Tool and Symbol," in which he emphasized that both physical tools and symbol systems culturally mediate human activity.

This perspective on the sociohistorical construction of human nature is also reflected in studies of the child as a "cultural invention," in which it is argued that the concept of "child" is a social and historical kind rather than a natural kind, and that children become what they are taken to be by others (e.g., Wartofsky, 1983).

I took up these issues in several different essays. In one (Pea, 1985a), I argued that computer tools serve not as they are often construed – as "amplifiers" of cognition – but as "reorganizers of mental functioning." The distinction highlighted the functional organization, or system characteristics, of human activity. Whereas amplification suggests primarily quantitative changes in accomplishments, what humans actually do in their activities changes when the functional organization of that activity is transformed by technologies.

(I explicate some of these functional shifts later in a section on Polya and distributed intelligence.)

In another essay speculating on integrating human and computer intelligence, I took a Vygotskian perspective on this question (Pea, 1985b), asking whether future computer systems could serve interactively, as adults and more able peers do now, to help guide children through zones of proximal development (ZPD), co-constructing with children their latent developmental capabilities. The central idea that emerged from these considerations was a radical one – that of considering the child–computer system as the developmental unit. I suggested an extension of the Turing test for assessing computer intelligence by means of an inability to differentiate interactive dialogues with the output of a human and that of a computer. In this extension, applied to the developmental level of the child–computer system outputs rather than the unsupported child, one would look for answers to queries concerning tasks defined to represent thinking of particular developmental levels for a child–computer system versus a child alone.

I further distinguished between “pedagogic systems,” or uses of computers that focus on achieving the cognitive self-sufficiency of their users, and “pragmatic systems, which allow for precocious intellectual performances of which the child may be incapable without the system’s support” (Pea, 1985b, p. 84). More recently, Salomon, Perkins, and Globerson (1991) have echoed this distinction in their characterization of effects *of* technology and effects *with* technology, a contrast to which I will return.

Getting to distributed intelligence

Since those essays were written, there has been a substantial increase in the density and novelty of computer technologies that play important roles in augmenting human activities, in science, industry, and education. Of special relevance to distributed intelligence is the increasing use of visualization techniques in scientific inquiry.

Augmenting intelligence with computing

In the case of science visualization, throughout many university and industrial research laboratories, groups and individuals are

achieving their desired activities through the use of high-resolution graphics programs, often involving supercomputers, which provide manipulable “virtual realities” (Lanier, 1989; Rheingold, 1991) for modeling and reasoning about domain phenomena in science, engineering, mathematics, and design (Brooks, 1988). In this paradigm, graphic computer representations have “direct manipulation” interfaces (Hutchins, Hollan, & Norman, 1986) with action properties analogous to their real-world counterparts. Human intuitions about how to act are exploited in communication with the machine in order to narrow gaps between desires and actions.

From such labs as that of the University of North Carolina at Chapel Hill, VPL Research, National Center for Supercomputing Applications at University of Illinois, Urbana-Champaign, and NASA AMES Research Center, scientific visualization examples include topics as diverse as molecular “docking” in molecular engineering (Ouh-Young, Pique, Hughes, Srinivisan, & Brooks, 1988), travel through virtual buildings before they are constructed (Brooks, 1986), and a study of a numerically modeled severe storm (Wilhelmson et al., 1990). Furthermore, modeling and interpretation of patterns in complex empirical data in biomedical research, space exploration, geophysics, molecular modeling, and robotics have come to depend on three-dimensional (3-D) graphic rather than numerical data displays, and new 3-D designs for structuring information displays exploit human visualization skills as well (Card, Robertson, & Mackinlay, 1991). The veridicality of many of these aesthetically elegant interfaces to complex knowledge are so striking that they have come to be designated as “virtual realities” in which highly complex phenomena can be modeled, explored, and experienced in lush color and dynamics well suited to the categorizing and pattern recognition capabilities of the human visual system (Blattner & Dannenberg, 1991) and, in some cases, the proprioceptive feedback that is provided. For example, take the following description of a 1991 SIGGRAPH course by Richard Becker of AT&T Bell Laboratories:

Consider for example, measurements of temperature, humidity, barometric pressure, percentage of cloud cover, solar radiation intensity, and wind speed at a particular location at noon on 100 different days. The data on these six non-spatial variables consist of 100 points in a six-dimensional space. In this course, participants peer into such six-dimensional spaces, see the configuration of points, and visualize them to understand their complex relationships.

Note in applications of advanced computing such as these how symbiotic are the contributions of the scientist formulating the problems and comparisons of interest, the designers of visualization algorithms, and the contributions of computation and display technologies.

While such applications are beyond most K-12 settings, nonetheless dynamic 2-D and, occasionally, 3-D graphic interfaces contribute to learning and reasoning in mathematics and science education. Perhaps most striking is the use in thousands of classrooms of microcomputer-based laboratories with which students can investigate real-world phenomena by means of data collection using probes that plug into the computer for such variables as temperature, pressure, light, and sound, with the generation of graphs to be interpreted as the results of these investigations (Linn, in press; Thornton & Sokoloff, 1990; Tinker, 1992). Again, consider the contributions made by the teacher and curriculum materials to the framing of the learner's investigations, the learner's perceptual and interpretive processes for looking at graphs, the technology collecting data and transferring them into data displays, and the designers behind these innovations. Similarly striking advances have been made in developing computer tools for learning statistics in middle schools and high schools through building and manipulating statistical models of populations (Hancock & Kaput, 1990; Rubin, Rosebery, Bruce, & DuMouchel, 1988; Rubin et al., 1990; Russell & Corwin, 1990),⁶ or for learning Newtonian physics in elementary schools (White, 1988; White & Horwitz, 1987). In each case, researchers and educators have been surprised at the young age at which learners can participate in treatments of complex subject matter.

Augmenting intelligence with guided participation

There has also been much work on designing new social arrangements and activity structures to support human learning, much of it inspired by Vygotskian (1978) and neo-Vygotskian conceptions of the ZPD, which argue that development occurs as the "internalization" of socially distributed cognitive processes in a "zone of

⁶ Spatial location, shape, color, brightness, and motion are used in commercial statistics programs such as Data Desk, MacSpin, StatView, and Systat for visualizing complex empirical phenomena and equations.

proximal development," toward autonomous performance (Brown, Chapter 7, this volume; Newman, Griffin, & Cole, 1989; Rogoff, 1990). In these conceptions of social contexts of cognitive development, adults often provide supported situations for children to perform more complex tasks than their current knowledge and skills alone would allow. Such "guided participation" (an apt phrase used by Rogoff, 1990) distributes the intelligence required to carry off the activity across child and adult. Affiliated work has elaborated a model of learning through reciprocal teaching and cognitive apprenticeships in which intelligence required to do an activity (e.g., interpret a text) is distributed across a group of peers, or a learner-mentor system (Brown, Collins, & Duguid, 1989; Collins, Brown, & Newman, 1989), as exemplified by instructional studies in reading (Palincsar & Brown, 1984), text composition (Bereiter & Scardamalia, 1986), college mathematics problem solving (Schoenfeld, 1985), and learning how to reason in geometrical optics (Pea, in press; Pea, Sipusic, & Allen, in press).

Augmenting intelligence with inscriptional systems

It is widely recognized that external representational systems, dependent on inscriptional technologies such as paper and pencil, computer and display, have made major contributions to the socio-historical development of science, mathematics, and other disciplines (e.g., Cassirer, 1923; Goodman, 1978). I use the phrase "inscriptional systems" rather than "symbol systems" or "representational systems" for two reasons. First, I want to stress their external, in-the-world status, which allows for construction, review, deconstruction, and the emergence of completed structures of inscriptions that have little relation to their patterns of temporal development (Latour & Woolgar, 1986; Lynch & Woolgar, 1990). Second, both "symbol" and "representation" have taken on the cognitive sciences interpretation of *mental* representation, deemphasizing the sociohistorical fact that many of the kinds of notations that are considered to be among the languages of "thought" – such as mathematical language, written language, and scientific symbols – began their existence ontogenetically as external inscriptions whose conventions of construction, interpretation, and use in activities had to be acquired in cultural activities.

We know that inscriptional systems often pose vast problems for the learner. Mapping relations between objects in the world and the written number system are problematic for many learners, as in the well-documented difficulties of place-value subtraction or, for older learners, between algebra equations or linguistic descriptions of situations and their representation in the notation of Cartesian coordinate graphs (Confrey, 1990). Inscriptions rarely reveal their affordances for activity. It is too rarely recognized that inscriptional systems, while allowing for efficient achievement of certain goal-directed activities, also make those very activities opaque to persons not privy to the conventions for their interpretation and use, an unfortunate circumstance for learning mathematics and science. The affordances of many inscriptional systems are deeply cultural in the following sense: A person has to have been introduced to, and preferably to have participated in, the activities that give meaning to these inscriptions. After such initiations, one may have the sense of directly perceiving the patterns the inscriptional system was designed to make "obvious," but before such initiation, the conventions and uses of the inscriptions are usually obtuse. Mature users of an inscriptional system know the kinds of tasks it is good for – the questions it enables them to answer, the inferences it enables them to make – as well as its limitations. Much of this is invisible to the initiate, since such social practice does not lie "in" the representation itself, but in its roles in relation to the activities of persons in the world.

People often invent inscriptional systems for local purposes, to achieve activities that would be harder to accomplish without them. For example, in describing a microgenetic study of adolescents' invention of a notational scheme for describing velocity and acceleration, di Sessa et al. (1991) characterized the increasing sophistication of the notation as one of "transparency" or obviousness to their intended purpose. He described the talents the students revealed in describing the pros and cons of the inscriptional systems that different students invented during the several-hour session as "metarepresentational knowledge." He demonstrated how the different kinds of inscriptional systems the students invented required more or less explanation for peers to be able to interpret the mapping from inscription to the situation depicted. I argue that we see the concept of efficiency of action, and the closing of the gap from desire to achieve-

ment, as important contributors to the normative assessments of "better" inscriptional systems (Pea, 1992).

Augmenting intelligence with situated cognition

Diverse studies, primarily on the basic mathematical reasoning that is embedded in such activities as the order loading of dairy workers (Scribner, 1985), grocery shopping (Murtaugh, 1985), and home dieting measurement activities (de la Rocha, 1986) and various street-life activities, such as street candy selling by Brazilian children (Carraher, Carraher, & Schliemann, in press; Saxe, 1988, 1990), began to reveal the powerful ways in which people use structural properties of the physical environment to carry some of the weight of what is traditionally "mental" activity in school-based mathematics tasks (Lave, 1988; Lave, Murtaugh, & de la Rocha, 1984). For example, in grocery store best-buy shopping, when mathematics is used at all, it is virtually always correct and creative in its uses of material features of unit sizes to save "mental" work in computation (Lave et al., 1984). Similar findings on exploitation of the environment to help in the doing of intelligence are provided by work on ecological memory in repetitive work tasks such as those involved in barhopping and waiting on tables (see Scribner, 1986). Such studies highlight how intelligence efficiently uses resources, drafting, or crafting the environment to achieve activity with less mental effort if necessary. These studies highlight the situated properties of everyday cognition, which is highly inventive in exploiting features of the physical and social situation as resources for performing a task, thereby avoiding the need for mental symbol manipulations unless they are required by that task. Empirical domains in which these conceptions have been further developed include reasoning about algebraic functions on a physical winch (Greeno, 1991), team navigation of a large ship (Hutchins, 1990), and carrying out photocopying tasks (Suchman, 1987).

The work on situated cognitive theory by Lave, Scribner, and others was richly descriptive and revealed aspects of human preference structures for relying on intelligence in the world in functional systems of activity. But that work did not go far enough in my opinion. It fell short in not acknowledging the fundamental roles of design in the activities of these reasoners and designers, in the achievement of

action through situated cognition. These studies also did not move from "is" to "ought" – for example, by recommending that learners be prepared by education to more deeply exploit situated knowledge for action in the world; nor did they, as Norman's (1988) work came to do, exhort designers to help learners function more effectively in the world.

Rich phenomena without a framework

I was struck by the lack of adequate conceptions of intelligence and its development to account for what was exciting and seemed to be working in new computer-enhanced work and learning environments, those studies involving new social arrangements for supporting learning, and accounts of the situated properties of everyday cognition. But what was the link?

The missing orientation came to me as I was reflecting on a story told by Seymour Papert at a meeting of National Science Foundation project officers in 1987. Papert (1980) had provided extensive neo-Piagetian arguments that when, in instruction-centered learning, one directly teaches a learner something, one robs that learner of the opportunity to discover it for him- or herself. This constructivist argument⁷ has been quite influential in designs for educational technology use in schools and in other curricular approaches. A version of this argument was made at this 1987 meeting by Papert concerning Logo-LEGO research. In this research, students built LEGO machines that could be controlled by Logo programs they wrote (Resnick & Ocko, 1990). Papert described what marvelous machines the students had built, with very little "interference" from teachers. On the surface, this argument was persuasive, and the children were discovering important things on their own. But on reflection, I felt this argument missed the key point about the "invisible" human intervention in this example – what the designers of LEGO and Logo crafted in creating just the interlockable component parts of LEGO machines or just the Logo primitive commands for controlling these machines. For there are only so many ways in which these components can be combined. Considerable intelligence has been *built into*

⁷ The MIT Epistemology and Learning Group now designates its pedagogical perspective as one of "constructionism" (e.g., Harel, 1990).

these interpart relations as a means of constraining what actions are possible with the parts in combination. What I realized was that, although Papert could "see" teachers' interventions (a kind of social distribution of intelligence contributing to the child's achievement of activity), the designers' interventions (a kind of artifact-based intelligence contributing to the child's achievement of activity) were not seen, were somehow not viewed as affecting the terms of the constructionist argument. But, of course, in either case the child was not engaged in solitary discovery, in keeping with the Piagetian metaphor of "child as scientist" – he or she could be scaffolded in the achievement of activity either explicitly by the intelligence of the teacher, or *implicitly* by that of the designers, now embedded in the constraints of the artifacts with which the child was playing.

Distributed intelligence mediated by design

What was thus missing, in my view, was an explicit recognition of the intelligence represented and representable in design, specifically in designed artifacts that play important roles in human activities. This led me to work on concepts and research explicitly concerning the notion of distributed intelligence around 1987 (Pea, 1988) and described in the present chapter.

Polya on problem solving and distributed intelligence

As an illustration of the ways in which conceiving of activity in terms of distributed intelligence reorients our perspectives on familiar phenomena, let us look at a set of familiar assumptions about the nature of problem solving from cognitive psychology. Specifically, let us briefly turn to a familiar model of problem solving from Polya's *How to Solve It* and explore how the concept of distributed intelligence relates to it. The standard problem-solving model, introduced by John Dewey (1910) early in the century and revised and popularized by the mathematician George Polya (1957), has been assimilated into the mainstream of cognitive psychology, appearing in most textbooks and accounts of problem solving. Many theorists have found its depiction in a six-stage model convenient (Figure 2.1). Research has shown the applicability of this model to writing, algebra word problem

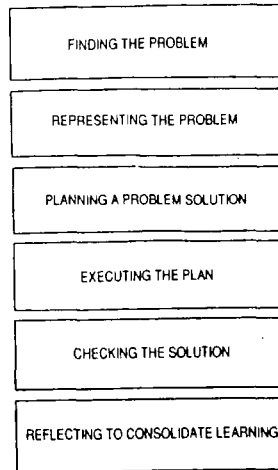


Figure 2.1. Six-stage problem-solving model.

solving, reading comprehension, electronics troubleshooting, programming, decision making, and many diverse tasks educators would like students to be able to do. It is important to note that these are not *linear* stages in a top-down process, but comprise a more *cyclic* system in which each new set of constraints created by materials the problem solver produces makes for new opportunities to be exploited in its next developments (as in writing; Pea & Kurland, 1987). This was the *first myth* to dissolve about the stages of problem solving.

The distributed-intelligence perspective provides reasons to explode a second and third myth intrinsic to the problem-solving model. Each involves dissolving the "boundaries" around the boxes.

The *second myth* is that the boxes in the model are constructions of the individual mind. Each phase may be, but is often not, the result of individual achievement. The role of others is crucial. In neo-Vygotskian research by Wertsch, McNamee, McLane, and Budwig (1980), we can see even "problem finding" as a social construction of the child with other agents, such as the mother who guides the child to "see" goals in the task of jigsaw-puzzle making. Similarly, in recent work on "anchored instruction," the Cognition and Technology

Group at Vanderbilt (1991) uses teacher guidance and carefully scripted videotapes of everyday problem solving to help students "see" the utility of concepts and strategies in mathematics and science for achieving activities in the world.

The *third myth* is that the different boxes in the model are mental constructions. They may be, but they are often not "tool-free." Crucial roles in mediating such phases of problem solving are played by external representations, features of the environment, and artifacts. "Planning a problem solution" is often mediated by external representations such as written language in lists or charts, or in diagrams serving as qualitative models of the problem situation. "Plan execution" is even automatically achieved through tools designed to save effort and to spare reliance on error-prone procedures (Engelbart, 1963; Rheingold, 1985).

So as we begin to ask, "What is distributed in distributed intelligence?" the boxes begin to crumble, and more complex formations of activity emerge:

1. Different whole-component processes of the problem-solving model (e.g., problem finding or problem representation) may be distributed in the environment, tools, or other persons. Whole task components are typically distributed during *collaborative activities* (e.g., one person may draft a topical plan as another finds materials to allow for writing) and *apprenticing* (e.g., Zinacanco weaver apprentices take on part activities such a boiling thread before learning to cut fabrics for sewing; Greenfield & Lave, 1982).
2. Parts of a whole-component process may be distributed as social constructions or as a result of processes of human-tool symbiosis (e.g., an outlining program and I work together to plan for text composition). In the social construction of plan execution during the single-word period, mother and child may build together a sentence that describes the present situation (Keenan, Schieffelin, & Platt, 1976).

Let us look more specifically at some of the ways intelligence is distributed with respect to the problem-solving model.

Problem finding. Goal cues are distributed in one kind of "problem finding." The need to recall what to do at an appropriate time or to cope with an overload of goals one wishes to maintain in working

memory is often overcome by the use of artifacts (e.g., alarms, lists), mnemonic strategies using environmental features (such as reminder objects put in key locations), or other persons. A software program may provide timely cues to the different subtasks of writing or to planning a project development and delivery schedule. And in some structured curricula, "problem-finding" aspects of distributed intelligence are distributed in the text as adjunct questions to the reader.

Problem representation. Humans often opportunistically use available objects, artifacts, or notes in representing problems – for example, milk crates are used by dairy loaders as calculating units (Scribner, 1985). A few examples will provide an illustration. In the well-known "cottage cheese" example, a weight watcher in the kitchen multiplies $\frac{2}{3}$ by $\frac{3}{4}$ through physical objects and divisions rather than symbol multiplication (de la Rocha, 1986). Requiring specification of units, the software program Semantic Calculator helps students represent problems in appropriate terms. As a social distribution of "problem representation," a teacher suggests that a student draw a diagram model of a problem before constructing equations to solve it. And rather than requiring the *creation* of representations, computer tools often offer different representations for *selection*. Mapping between problem representations may be done automatically instead of by the student (e.g., automatic graphing of algebraic functions is now available on inexpensive calculators).

Planning a problem solution. This is often made unnecessary as the gap between plan and plan execution is reduced to perceptual choice by severely reducing the number of choices. To save error and effort, algorithms for repetitive measurement or computations can be built into the artifact used to measure, so that applying the tool to the task is the needed action and "planning" becomes unnecessary. "Planning" a problem solution for riding a bicycle for the first time without falling over becomes unnecessary when training wheels are mounted. Research on learning to compose texts shows that it is easier to write well when one uses planning aides such as "completion" sentences: "My most important point was . . ." (Bereiter & Scardamalia, 1986).

Executing the plan. This is often distributed. Effortful, repetitive activities of "clerical cognition" are automated as algorithms, macros, and templates for execution with minimal thought or off-loaded onto tools or machines (Bush, 1945; Licklider, 1960). A typical word-processing macro might be to "find all occurrences of 'mind'; replace each with 'society of minds' in italics." Autochecking and autocorrection of typing mistakes are now features of many spell-checking programs. Social allocation of the part-component process of plan execution takes place in apprenticeship learning, too, and is used by analogy in recent work in artificial intelligence that sends computer "agents" off to do information retrieval. Prominent examples already in schools are strategy-supporting and outlining programs for writing and microcomputer-based laboratories that provide hardware-software systems for measuring and graphing changes over time in temperature, light, or sound. For a few hundred dollars there are programs that provide equation-solving "workbenches" that automatically do complex symbol manipulations, which are prone to error when carried out with paper and pencil.

Error checks of solutions. These are commonly distributed. The need to check for errors (e.g., in calculations or programming) is often obviated by blocking the very possibility of error. Error-prone activities are made impermissible to carry out in many systems of human-computer interaction (e.g., the computer queries whether I really want to throw away my word processor when I accidentally act to delete it).

With this introduction in mind, let me offer an unfamiliar but typical example of intelligence "embodied" in artifacts, distributed for use across history and minds.

An illuminating case

An example of distributed intelligence comes from the PBS television show "Square One" on mathematics for children. A forest ranger is being interviewed. Each year she measures the diameters of trees in the forest to estimate the amount of lumber contained in a plot of land. With a conventional measuring tape she

1. measures the circumference of the tree (6 feet);
2. remembers that the diameter is related to the circumference of an object according to the formula circumference/diameter equals $22/7$ (or π);
3. sets up the formula, replacing the variable circumference with the value of 6 feet;
4. cross-multiplies, getting $22(\text{diameter-unknown}) = 42$;
5. isolates the diameter by dividing by 22, obtaining $42/22$;
6. reduces the fraction $42/22$ to 1.9 feet.

Note that to do this she has to remember the formula, set it up correctly, and then correctly do her substitutions and calculations. This procedure is error- and effort-prone. She could learn to do this automatically. She could even ask someone nearby who happens to be good at estimating. But something different happens: A new measuring tape is invented. I call it a special-purpose "direct calculation" tape for tree-diameter measures. The numbers have been scaled so that the algorithm for these calculations is *built into* the tool. She wraps it around the tree and reads off "1.9 feet" directly. The only possible errors are perceptual ones (if she does not see the number clearly) or ones caused by the use of the tape for measuring purposes to which it was not adapted.

The work done by the new measuring tape helps explain why it is wrong to say that the person using it "represents the problem," "plans a problem solution," and "checks the solution." These three phases of the intelligent activity of measuring trees are distributed in the object used for measuring, its social history of practices for engaging that embodied intelligence, and the user's memory for how to engage that tool in activity.

This example illustrates that activity is a product not of intelligence in the individual mind, but of one's memory, the structure of the resources available in the environment at hand, and one's desires, which guide the interpretation of these structuring resources. Through processes of design and invention, we load intelligence into both physical, designed artifacts and representational objects such as diagrams, models, and plans. We exploit intelligence from objects when we use them instrumentally in activities. And we often need to decouple intelligence from such objects to reuse them in novel ways. Once such intelligence is designed into the affordance properties of artifacts, it

both guides and constrains the likely contributions of that artifact to distributed intelligence in activity. Obviously the measuring tape, once the formula has been compiled into its design, cannot readily be adapted to linear measurement without recrafting its scale.

Issues in distributed intelligence

A focus on distributed intelligence is now rare in learning or educational research. The common assumption of solo intelligence as a central goal of education guides the investigation of learning, the cultivation of mental abilities, information processing, the role of misconceptions in the acquisition of new knowledge, and the design of classroom instruction, with relative disregard for the social, physical, and artifactual surroundings in which such activities take place. Many schools, technology developers, and researchers now use technologies to "enhance" education by making the achievement of traditional objectives more efficient. Many intelligent tutors and software programs in mathematics and science fit together under this strategy. Objectives for education are not reconceptualized; the computer is conceived of as a means for "delivering" key components of instructional activity – not for redistributing intelligence and new uses of students' potentials for activity and participation.

Yet the phenomena of distributed intelligence make apparent how the exploitation of external resources changes the functional systems from which activity emerges. New resources, and changing attitudes toward the integrity of their use, change the properties of what one "needs to know." Culturally valued designs for distributed intelligence in which a learner participates to achieve a specific goal will change throughout history. Stated with a different focus, and as but one example, what is considered to be the curriculum will vary when the technologies used for reasoning in a domain change (Pea, 1987).

These shifts are particularly dramatic for mathematics. As one may observe in the new curriculum and evaluation standards proposed by the National Council of Teachers in Mathematics (NCTM), the support of computer technologies has dramatically transformed the objectives and timing of the entire course of mathematics education (NCTM, 1989). For example, in K–4 mathematics, a focus on long-division operations and paper-and-pencil fraction computation has

been diminished, the availability of calculators is assumed, and attention is shifted to estimation activities and a focus on the meaning of operations and the selection of appropriate calculation methods. In grade 9–12 mathematics, the presumed use of calculators, graphing utilities, statistical programs, and computer-based exploration of 2-D and 3-D figures and uses of coordinate and transformation approaches to geometry leads to recommendations for decreased attention to such activities as hand graphing of functions, paper-and-pencil solution of trigonometric equations, and axiomatic treatments of Euclidean geometry. The treatment of entirely new topics in statistics, probability, and discrete mathematics is made possible at these grade levels by visual and dynamic technological support for reasoning and learning in these areas. The NCTM standards go on to note that “calculators, computers, courseware, and manipulative materials are necessary for good mathematics instruction; the teacher can no longer rely solely on a chalkboard, chalk, paper, pencils, and a text” (1989, p. 253).

While the distributed nature of intelligence is everywhere noticeable, what consequences should these observations about distributed intelligence have for the design and practice of education? If we treat distributed intelligence in action (rather than the individual’s knowledge structures alone) as the scientific unit of analysis for research and theory on learning and reasoning, new questions arise:

1. What is distributed (i.e., different components of the problem-solving process as well as the product)?
2. What constraints govern the dynamics of such distributions in different time scales (e.g., microgenesis, ontogenesis, cultural history, phylogenesis)?
3. Through what reconfigurations of distributed intelligence might the performance of an activity system improve over time?
4. What distributions and their changes over time are effective for specific goals of education?

When we think about intelligence as manifest in activity and as distributed in nature, we may wish to ask a descriptive question for learning: How *do* learners enact the cultural practices for designing, constructing, and displaying distributed intelligence in activity? We must also ask the prescriptive version of this question for education:

How *should* learners acquire such cultural practices? To answer the latter question, we will need to examine trade-offs in the design of distributed intelligence that may influence our considerations.

Trade-offs in the design of distributed intelligence

It is important to observe and acknowledge distributed intelligence because successful learning (that which eventuates in the achievement of activities) often involves it and learning beset with failures often does not. Education often results in making far too many people look “dumb” because they are not allowed to use resources, whereas outside of education we all use resources. To get close to empowering more learners to do the activities that education should be enabling, intelligence should be recognized as distributed and education should elaborate the design consequences of that fact.

I have said much about design, perhaps too much for many psychologists and educators. But one central aspect of work in design is that it is very commonly posed, or at least thought about, in terms of *trade-offs*. A designed thing is, of course, but one choice among many possibilities that were considered, and even more possibilities that were never considered. Designers often are quite articulate about trade-offs (MacLean, Young, & Moran, 1989).

Why is a focus on trade-offs important? Because much of the critical discussion around distributed intelligence takes an extreme position on one or two dimensions of a design trade-off and over-emphasizes it at the cost of acknowledging the more basic point that trade-offs are inevitable in design. What we quickly come to see is that we have a long way to go in working on our own design space for considering the ways in which distributed intelligence relates to learning and education. There are no easy or obvious answers. And recourse, much less reliance, on existing practice is one of the weakest arguments of all. It makes it seem as if there is little choice but to yield to existing practice, when quite different arrangements may be possible, preferable, and even practical. It does not follow that they would be easy to achieve.

Let us consider several important trade-offs in thinking about designs of distributed intelligence as examples of these issues.

Trade-off 1: access to activity versus understanding its foundations. A central trade-off is that between *access* and *understanding* that may come from focusing on either tool-aided cognition or tool-unaided cognition. What opportunities are lost for learner participation in higher-level activities, and meaningful contributions rather than basic skills practice, if one does not allow for distributed-intelligence support for those activities involving artifacts and other persons? Tools may grant greater accessibility to complex mentation. More universal access among learners to participation in complex thought and activities may be gained at the expense of low-level understanding. An emphasis on learning activities requiring tool-unaided cognition may grant deeper understanding, but at the cost of blocking many individuals from engaging in meaningful whole-task problem solving because of the learning "overhead" of knowledge needed to get to the tool-unaided problem-solving process.

Whatever we find as scientists about how the dynamics of distributed intelligence work, we are still faced with the moral question of educational aims – whether they are to foster intelligence that it executed "solo," is tool-aided, or is collaborative, or in what combination for what content domains and activities. We are at a point in cultural history where these issues of tool-aided, socially shared cognition must be examined and debated on empirical grounds. What designs of distributed intelligence are effective to what ends? What are our assumptions about the patterns of distributed intelligence in society into which students must enter and productively use what they have learned?

In describing the theoretical significance of learner development being aided by both social and computational "scaffolds" to achieve more than the learner could alone, I argued some time ago:

Self-sufficiency is [not assumed to be] the telos of such learning activities. Many forms of cognitive activity may require the continuing intervention of an intelligent computer system, for effectiveness or because of their complexity. Similarly, not all cognitive tasks for which ZPDs can be arranged should be ones that the child is expected to internalize for subsequent solo performances. Solo performances are not realistic in terms of the ways in which intelligent activities are organized and accomplished in the real world. They are often collaborative, depend on resources beyond an individual's long-term memory, and require the use of information-handling tools. . . . The level of task understanding necessary for the child alone is an empirical question that remains to be answered, domain by domain. (Pea, 1985b, p. 84)

There has been a common objection to this intelligence-distribution intensive orientation that wishes to import the "efficiency drive" of everyday cognition into the classroom. For doesn't one get access to distributed intelligence at the cost of understanding and solo cognition? Doesn't such distributed intelligence make us look smarter than we are by building the clever constraints that guide the display of intelligent action as features of the social, computational, or representational environments? Along these lines, Salomon et al. (1991) distinguished two kinds of cognitive effects of technologies on intelligence: "Effects *with* technology obtained during intellectual partnership with it, and effects *of* it in terms of the transferable cognitive residue that this partnership leaves behind in the form of better mastery of skills and strategies" (p. 2). They argue for the educational utility of emphasizing effects *of* rather than *with*, so that autonomous intellectual performance can be achieved. For if not, they argue, the student is dependent on the technology, without which he or she does not understand.

The invisible nature of many tools and the support of social networks in collaboration, even those now used in the classroom, makes it apparent that this antisupport argument will not do. Pencils are allowed as memory aids, so why not have to do mathematics orally or reinvent measurement scales used in instrumentation? In the world outside school, part of knowing how to learn and solve complex problems involves knowing how to create and exploit social networks and the expertise of others, and to deftly use the features of the physical and media environments to one's advantage – like using principles of leverage and balance in judo. Socially scaffolded and externally mediated, artifact-supported cognition is so predominant that its disavowal in the classroom is detrimental to the transfer of learning beyond the classroom (also see Resnick, 1987).

Salomon et al. (1991) broach the issue of their potential conservatism in wedging the distinction between effects *with* and effects *of*, since with the widespread availability of intelligent computer tools "the question of what residues the partnership with the technology leaves might be moot" (p. 5). But they consider such tools not sufficiently prevalent yet, so "how a person functions away from intelligent technologies must be considered" (p. 5), and emergent dilemmas in the world "need an independent and capable thinking mind" (p. 5). This insistence profoundly misses several

critical points concerning distributed intelligence. I have never argued that "all we should aim at are effects *with* a technology whereby intelligence is truly distributed" (p. 5). One neglected point is that distributed intelligence is largely invisible throughout life, but is broadly considered, as I have argued, to include not only computer tools, as they emphasize, but materials in the environment and the expertise available from other human beings. A second point is that this distributed intelligence is quite commonly *designed*, with consequences described in a later section. A third is that we may all want to exert a greater voice in the design of distributed intelligence, both in and out of schooling, once we recognize the designedness of intelligence. And a fourth point is that a central goal for an empowering education is to nurture the learners' attitudes and talents in designing distributed intelligence for their use and that of others, not only to participate in the designs of distributed intelligence provided by others. Finally, the general argument attributed to me that is tacit in their critique – that all thinking *should* be distributed – is wildly wrong. Of course, there will not be intelligent computer tools for every kind of task achievement conceivable, nor should there be.

Trade-off 2: static definition of tasks versus evolving concepts of tasks. One potential misunderstanding of the concept of distributed intelligence must be guarded against. It is the notion of distribution as *reallocation*, of dividing up cognition among mind, setting, and artifacts, or a "division of labor" among contributions to distributed intelligence. This limited notion is that there is a fixed quantity of intellectual work for the doing of some task and that this quantity can then be differentially distributed across persons and environment. The concept we are concerned with is that of *expanding* intelligence rather than reallocating it. We want to ask where the capacity for innovation exists in the concept of distributed intelligence, how we may engender ever more useful designs for distributed intelligence – whether we are considering shared activities such as cooperative learning or an individual's uses of a tool for augmenting mathematical problem-solving ability. I have argued that there is a natural tendency for humans to aspire to greater efficiency in distributing intelligence through the design and use of the physical, symbolic,

and social environments in order to cope with the complexity of "mental activities." But this does not lead to a situational determinism. The flip side of this efficiency drive is the *freedom* thereby attained to explore and seek the new. Having achieved a greater efficiency by off-loading thinking into the design of the world, one then is freed up to continue to invent and innovate. Whether learning conditions foster these new opportunities is an issue of cultural choice.

Salomon et al. (1991) make an interesting contrast between two ways of evaluating intelligence for partnerships between people and technologies: *systemic* and *analytic*. The systemic attends to the aggregate performance of the person-computer system, while the analytic articulates the specific contributions made by the person and the technology to that performance. They caution against the possibilities of human deskilling and disinterest in tasks if analytic analyses reveal minimal contributions of the person to the system performance. However, this analysis appears to buy too deeply into the fixed-quantity concept.

Further, they argue mistakenly that the analytic approach is "more oriented toward the study of human potential and toward educational concerns" (p. 5) than the systemic approach, which "appraises the products of the joint abilities of person and tool." This is simplistic in at least two ways. One is in terms of the access-understanding trade-off discussed earlier – the systemic approach may be profoundly suited to education by enabling all learners to do things that would be accessible to only some learners if the analytic approach had its way. The second is that the learner may be not just the *recipient* of the intellectual tool, which contributes to high-level systemic achievement, but its *designer* – and that learner may minimize the need to contribute his or her mental activities to that performance by design. In the former case, a too conscious reliance on the analytic approach may bode ill for enabling poorly motivated and low-achieving students to engage successfully in high-level tasks to which the computer contributes. In the latter case, a too restrictive use of the analytic approach may lead to a neglect of the mindful process by which the learner designs distributed intelligence so as to make minimum use of mental process for system performance involving the computer tool.

There are various ways to overcome the deskilling problems mentioned as well, even if one were (which I am not) inclined to accept a fixed-quantity concept of intelligence contributing to task achievement by a human-computer system. First, one could treat *design* seriously and rotate the component activities (as in the six-phase problem-solving process described earlier) contributed by the human and the computer, with the objective of avoiding the possibilities of an entrapping and boring contribution of the same component activities to that task by the human. Unfortunately, some of those phases, such as problem finding and problem representation, may prove immensely difficult for the computer to contribute to the system performance. Second, I have already stressed the design aspect of distributed intelligence, one normative consequence of which involves an increasingly recognized phenomenon in the world of work – the need to “informatize” (rather than automate) the workplace (Zuboff, 1988), thereby providing important opportunities for workers to contribute to the redesign of their working conditions and tools (Attewell, 1987; Barley, 1988; Bjerknes, Ehn, & Kyng, 1986; Wenger, 1991). Finally, taking a lesson from Kusterer’s (1978) findings of individual differences in knowledge on the job among “unskilled workers,” we would design activities that allowed participation in diverse tasks for knowledge utilization, and with as few routinized tasks as possible. Kusterer finds broader working knowledge for workers who often need to learn new things to resolve emergent dilemmas in their nonroutine work functions.

Why does the static versus dynamic definition of tasks exemplify a trade-off? Because it may be easier to develop learning materials and teacher education programs for helping students achieve static tasks, whereas if the very tasks learners undertake evolve as the tools and designs for distributed intelligence change over time, static materials and teacher preparation methods for the “delivery” of curriculum will not suffice. The trade-off becomes one of automating the delivery of standard materials and practice to the neglect of the dynamic nature of distributed intelligence versus providing continually renewable, flexibly adaptive materials and practices.

Evolving telos: new aims of development

One of the central implications of the dialectical perspective on human nature arises when we look at the concept of development

itself. Piaget sketched a view that was neo-Kantian in nature and rooted in a well-defined endpoint of formal operations (Piaget & Inhelder, 1969). By contrast, the implications of the sociohistorical view of human nature, which is manifest in a focus on the design of distributed intelligence, are more profoundly open-ended. When “development” is seen not as a descriptive concept standing in for “time” or “history,” but as a *normative* concept involving the evaluation of means-end adaptations (Kaplan, 1983), and an activity-person system is defined as more or less highly developed with respect to the achievement of these ends, it becomes apparent that the system’s developmental status is sociohistorically defined in terms of society’s evolving metrics of evaluating means-end relations and in the ends selected themselves.

Developmental psychology thus takes on a different character when considered from this orientation. Whether under Piagetian influences or those of an information-processing approach, developmental studies have typically targeted changes in the mental structure and processes of the individual. Although social scaffolding of development is a definite emphasis in research influenced by the sociohistorical school of Vygotsky, Luria, and Leont’ev, more attention has been paid in the recent incarnations of that work to social scaffolding than to the roles of cultural artifacts and representations as carriers of intelligence (e.g., Moll, 1990; Wertsch, 1985, 1991). This is a particularly important omission in light of arguments such as those of Wartofsky (1979) that the artifact is to cultural evolution what the gene is to biological evolution – the vehicle of information across generations. Answers to the question of what develops may fundamentally change in the face of a distributed-intelligence perspective, for *systems of activity* – involving persons, environment, tools – become the locus of developmental investigation.

What I have been stressing throughout is a focus on intelligence as manifest in *activity* – dynamics, not statics. The language used by Salomon et al. (1991) to characterize the concepts involved in how they think about distributed intelligence is, by contrast, *entity-oriented* – a language of containers holding things. “Cognitive residues” are “left behind” by interactions with technologies or “carried away” from human-computer partnerships. Abilities and intelligence are “in” persons or tools. When one views intelligence as *in* activity, which I argue for in this chapter – rather than in agents or tools – the kind

of clean, pure, solo intelligence of the independent and capable thinker that Salomon et al. seek to produce from education is but a theoretician's fantasy. Persons are situated in the physical, artifactual, and social worlds and continually use and redesign them to achieve the activities they desire. The distributions they so chose to design or participate in may change over time, cultural as well as ontogenetic. How social models and social pressures, and individual desires and aesthetics, come to shape these changing patterns of distribution over time is a reformulation of the basic question of developmental psychology.

Broader consequences

There are some other noteworthy consequences of this perspective on intelligence beyond education. The scope of coverage is intentionally broad and recasts a broad variety of contemporary and historical issues (Pea, 1993). These include the impacts of text literacy on thinking; the influences of symbol systems in mathematics, logic, and science on forms of thought and activity; relations among changes in science, technology, and society (e.g., the effects of industrialization on work and the distribution of control), and new paradigms in computing, publishing, and telecommunications (Pea & Gomez, 1992). These are critical issues, since few technological inventions besides computers (and affiliated technologies involving microprocessors) have had or will continue to have as profound an impact on how people spend their time in work and on how new educational objectives are defined (Dunlop & Kling, 1991).

Seeking to understand distributed intelligence may be important because it yields sociohistorical links beyond the confines of today's cognitive science of education. For example, its results will tie into design more generally. Architects and designers are often sensitive to how human activities emerge and flow by the shapes that an environment affords (e.g., Alexander, Ishikawa, Silverstein, & Jacobson, 1977; also see Hooper, 1986). I have highlighted the sociohistorical fact that the world has been shaped by the intelligence that has been "left behind" through the activities of past persons (in artifacts, conventions, practices) and that is continually being transformed by so-

cial agents forming the current collectivity of intelligence, mediated by the individual and situated interpretation of meaning that forms the fabric of creativity and development.

Learning and design are fundamentally connected with an orientation toward distributed intelligence. Exploration and play, basic human capacities used long before the invention of today's education, are seen as important, as particular desires leading to designs of distributed intelligence. Learning can be viewed as much more than "problem solving" and more broadly in terms of each of the desires. For example, the activities of play as much create and find problems as they "solve" them. Technology design and development are also viewed differently. New technologies can support human activities by serving as experimental platforms in the evolution of intelligence – by opening up new possibilities for distributed intelligence. They are not serving, in any simple sense, as "amplifiers of intellect" or as ways to "mechanize" existing desires (e.g., off-loading particular kinds of activity in work).

Conclusions

When we look at actual human practices, we see that human cognition aspires to efficiency in distributing intelligence – across individuals, environment, external symbolic representations, tools, and artifacts – as a means of coping with the complexity of activities we often call "mental."

Since such aspirations do not inevitably lead to the fulfillment of culturally valued goals of invention and innovation in the face of today's rapid societal and global change, a principal aim of education ought to be that of *teaching for the design of distributed intelligence*. Learning to create and willfully regulate distributed intelligence should be an aim of education for students and teachers. We should reorient the educational emphasis from individual, tool-free cognition to facilitating individuals' responsive and novel uses of resources for creative and intelligent activity alone and in collaboration. Such an education would encourage and refine the natural tendency for people to continually re-create their own world as a scaffold for their activities. For example, in mathematics and science education, one might develop a metacurriculum oriented to learning about the role

of distributed intelligence in enabling complex thought. Students would come to understand and deploy heuristics for inventing cognitive technologies as participants in a knowledge-using community. They would see through their activities where the bottlenecks of complex mentation reside. They would recognize how physical, symbolic, and social technologies may provide the supports necessary for reaching conceptual heights less attainable if attempted unaided. This goal might be achieved through the examination of living, everyday examples (building from cases where they already do distributed intelligence in the world) and, perhaps, through case studies of the roles of information structures (e.g., matrices, flow charts, templates) and social structures (work teams, apprenticeships) in mediating learning and reasoning as activity systems of distributed intelligence. Students would be empowered both through the reflective use of new tools and through the invention of new tools and social distributions of activities.

In sum, we should strive toward a reflectively and intentionally distributed intelligence in education, where learners are inventors of distributed-intelligence-as-tool, rather than receivers of intelligence-as-substance. In the court of worldly experience, such learners may be far more ready not only to adapt to change but to contribute substantially to it.

References

- Agre, P. (in press). *Computation and human experience*. Cambridge University Press.
- Alexander, C., Ishikawa, S., Silverstein, M., & Jacobson, M. (1977). *A pattern language: Towns, buildings, construction*. New York: Oxford University Press.
- Allen, C. (1988). *Situated designing*. Unpublished master's thesis, Carnegie-Mellon University, Pittsburgh, PA.
- Atwell, P. (1987). The deskilling controversy. *Work and Occupations*, 14, 327-46.
- Barley, S. (1988). Technology, power, and the social organization of work: Toward a pragmatic theory of skilling and deskilling. *Research on the Sociology of Organizations*, 6, 33-80.
- Barthes, Roland. (1972). *Mythologies*, trans. A. Lavers, New York: Hill & Wang.
- Bateson, G. (1972). Form, substance, and difference. In *Steps to an ecology of mind* (2d ed.). New York: Ballantine Books.
- Bereiter, C., & Scardamalia, M. (1986). *The psychology of written composition*. Hillsdale, NJ: Erlbaum.
- Bjerknes, G., Ehn, P., & Kyng, M. (Eds.). (1986). *Computers and democracy: A Scandinavian challenge*. Brookfield, VT: Gower.

- Blattner, M., & Dannenberg, R. (Eds.). (1991). *Multimedia and multimodal user interface design*. Reading, MA: Addison-Wesley.
- Brooks, F. (1986). Walkthrough: A dynamic graphics system for simulating virtual buildings. *Proceedings of the ACM Workshop on Interactive Graphics*, 9-21.
- (1988). Grasping reality through illusion: Interactive graphics serving science. *Proceedings of the ACM SIGCHI Human Factors in Computing Systems Conference*, 1-11.
- Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, 18 (1), 32-42.
- Bush, V. (1945, July). As we may think. *Atlantic Monthly*, 101-8.
- Card, S. K., Robertson, G. G., & Mackinlay, J. D. (1991, April-May). The information visualizer, an information workspace. In S. P. Robertson, G. M. Olson, & J. S. Olson (Eds.), *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*, 181-8.
- Carraher, T. N., Carraher, D. W., & Schliemann, A. D. (in press). *Street mathematics and school mathematics*. Cambridge University Press.
- Cassirer, E., (1923). *Substance and function & Einstein's theory of relativity*. New York: Dover.
- Cognition and Technology Group at Vanderbilt (1990). Anchored instruction and its relationship to situated cognition. *Educational Researcher*, 19 (6), 2-10.
- Collins, A., Brown, J. S., & Newman, S. (1989). Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser*. Hillsdale, NJ: Erlbaum.
- Confrey, J. (1990). A review of the research on student conceptions in mathematics, science, and programming. *Review of Research in Education*, 16, 3-56.
- de la Rocha, O. (1986). *Problems of sense and problems of scale: An ethnographic study of arithmetic in everyday life*. Unpublished doctoral dissertation, University of California, Irvine.
- Dewey, J. (1910). *How we think*. Boston: Heath.
- di Sessa, A. A., Hammer, D., Sherin, B., & Kolpakowski, X. (1991). Inventing graphing: Meta representational expertise in children. *Journal of Mathematical Behavior*, 10, 117-60.
- Dunlop, C., & Kling, R. (Eds.). (1991). *Computerization and controversy: Value conflicts and social choices*. New York: Academic Press.
- Engelbart, D. (1963). A conceptual framework for the augmentation of man's intellect. In G. W. Howerton & D. C. Weeks (Eds.), *Vistas in information handling, Vol 1: The augmentation of man's intellect by machine* (pp. 1-29). Washington, DC: Spartan Books.
- Ford, M. E., & Nichols, C. W. (1987). A taxonomy of human goals and some possible applications. In M. E. Ford & D. H. Ford (Eds.), *Humans as self-constructing living systems: Putting the framework to work*. Hillsdale, NJ: Erlbaum.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.
- (1982). *Reasons for realism: Selected essays of James J. Gibson*. Hillsdale, NJ: Erlbaum.

- Goodman, N. (1978). *Ways of worldmaking*. Indianapolis, IN: Hackett.
- Greenfield, P. M., & Lave, J. (1982). Cognitive aspects of informal education. In D. Wagner & H. Stevenson (Eds.), *Cultural perspectives on child development* (pp. 181-207). San Francisco: Freeman.
- Greeno, J. G. (1991). Environments for situated conceptual learning. In L. Birnbaum (Ed.), *Proceedings of the International Conference on the Learning Sciences* (pp. 211-16). Charlottesville, VA: Association for the Advancement of Computing in Education.
- Hancock, C. M., & Kaput, J. J. (1990). Computerized tools and the process of data modeling. *Proceedings of the 14th International Congress on the Psychology of Mathematics Education*.
- Harel, I. (Ed.). (1990). *Constructionist learning*. Cambridge, MA: MIT Media Laboratory.
- Hooper, K. (1986). Architectural design: An analogy. In D. A. Norman & S. W. Draper (Eds.), *User centered system design: New perspectives on human-computer interaction* (pp. 9-23). Hillsdale, NJ: Erlbaum.
- Hutchins, E. (1990). The technology of team navigation. In J. Galegher, R. E. Kraut, & C. Egido (Eds.), *Intellectual teamwork: Social and technological foundations of cooperative work* (pp. 191-220). Hillsdale, NJ: Erlbaum.
- Hutchins, E. L., Hollan, J. D., & Norman, D. A. (1986). Direct manipulation interfaces. In D. A. Norman & S. W. Draper (Eds.), *User centered system design: New perspectives on human-computer interaction* (pp. 87-124). Hillsdale, NJ: Erlbaum.
- Kaplan, B. (1983). Genetic-dramatism: Old wine in new bottles. In S. Wapner & B. Kaplan (Eds.), *Toward a holistic developmental psychology* (pp. 53-74). Hillsdale, NJ: Erlbaum.
- Keenan, E., Schieffelin, B., & Platt, M. (1976). Propositions across speakers and utterances. *Papers and Research on Child Language Development*, 12, 127-43.
- Kusterer, K. C. (1978). *Know-how on the job: The important working knowledge of "unskilled" workers*. Boulder, CO: Westview.
- Lanier, J. (1989). Plenary address on virtual reality. *Proceedings of UIST: The Annual ACM SIGGRAPH Symposium on User Interface Software and Technology*.
- Latour, B., & Woolgar, S. (1986). *Laboratory life: The construction of scientific facts* (2d ed.). London: Sage.
- Lave, J. (1988). *Cognition in practice: Mind, mathematics and culture in everyday life*. Cambridge University Press.
- Lave, J., Murtaugh, M., & de la Rocha, O. (1984). The dialectics of arithmetic in grocery shopping. In B. Rogoff & J. Lave (Eds.), *Everyday cognition: Its development in social context*. Cambridge, MA: Harvard University Press.
- Leont'ev, A. N. (1978a). *Activity, consciousness, and personality*. Englewood Cliffs, NJ: Prentice-Hall.
- (1978b). The problem of activity in psychology. In J. V. Wertsch (Ed.), *The concept of activity in Soviet psychology* (pp. 37-71). White Plains, NY: Sharpe.
- Licklider, J. C. R. (1960). Man-computer symbiosis. *IRE Transactions on Human Factors in Electronics, HFE-1*, 4-11.

- Linn, M. C. (in press). The computer as lab partner: Can computer tools teach science? In L. Roberts, K. Sheingold, & S. Malcolm (Eds.), *This year in school science 1991*. Washington, DC: American Association for the Advancement of Science.
- Luria, A. R. (1979). *The making of mind: A personal account of Soviet psychology*. Cambridge, MA: Harvard University Press.
- Lynch, M., & Woolgar, S. (Eds.). (1990). *Representation in scientific practice*. Cambridge, MA: MIT Press.
- MacLean, A., Young, R., & Moran, T. (1989). Design rationale: The argument behind the artifact. *Proceedings of CHI'89: Human Factors in Computing Systems, April 30-May 4, Austin, Texas* (pp. 247-52). New York: Association for Computing Machinery.
- Moll, L. C. (Ed.). (1990). *Vygotsky and education*. Cambridge University Press.
- Murtaugh, M. (1985). The practice of arithmetic by American grocery shoppers. *Anthropology and Education Quarterly*, 16, 186-92.
- National Council of Teachers in Mathematics (1989). *Curriculum and evaluation standards for school mathematics*. Reston, VA: NCTM.
- Newman, D., Griffin, P., and Cole, M. (1989). *The construction zone: Working for cognitive change in school*. Cambridge University Press.
- Norman, D. (1988). *The psychology of everyday things*. New York: Basic Books.
- Ouh-Young, M., Pique, M., Hughes, J., Srinivisan, N., & Brooks, F. (1988). Using a manipulator for force display in molecular docking. *IEEE Robotics and Automation Conference*, 3, 1824-9.
- Palincsar, A., & Brown, A. L. (1984). Reciprocal teaching of comprehension-fostering comprehension-monitoring activities. *Cognition and Instruction*, 1, 117-76.
- Papert, S. (1980). *Mindstorms*. New York: Basic Books.
- Pea, R. D. (1985a). Beyond amplification: Using computers to reorganize human mental functioning. *Educational Psychologist*, 20, 167-82.
- (1985b). Integrating human and computer intelligence. In E. L. Klein (Ed.), *New directions for child development: No. 28, Children and computers* (pp. 75-96). San Francisco: Jossey-Bass.
- (1987). Cognitive technologies for mathematics education. In A. Schoenfeld (Ed.), *Cognitive science and mathematics education* (pp. 89-122). Hillsdale, NJ: Erlbaum.
- (1988). *Distributed intelligence and education* (Technical rep.). Palo Alto, CA: Institute for Research on Learning.
- (1992). Augmenting the discourse of learning with computer-based learning environments. In E. de Corte, M. Linn, & L. Verschaffel (Eds.), *Computer-based learning environments and problem-solving* (NATO Series, subseries F: Computer and System Sciences). New York: Springer.
- (1993). *Distributed intelligence*. Unpublished manuscript, Northwestern University, Evanston, IL.
- Pea, R. D., & Gomez, L. (1992). Distributed multimedia learning environments. *Interactive Learning Environments*, 2(2), 73-109.

- Pea, R. D., & Kurland, D. M. (1987). Cognitive technologies for writing development. In L. Frase (Ed.), *Review of Research in Education* (Vol. 14, pp. 71–120). Washington DC: AERA Press.
- Pea, R. D., Sipusic, M., & Allen, S. (in press). Seeing the light on optics: Classroom-based research and development for conceptual change. In S. Strauss (Ed.), *Development and learning environments*. Norwood, NJ: Ablex.
- Piaget, J., & Inhelder, B. (1969). *The psychology of the child*. New York: Basic Books.
- Polya, G. (1957). *How to solve it: A new aspect of mathematical method* (2d ed.). Garden City, NJ: Doubleday.
- Resnick, L. (1987). Learning in school and out. *Educational Researcher*, 16 (9), 3–21.
- Resnick, M., & Ocko S. (1990). LEGO/Logo: Learning through and about design. In I. Harel (Ed.), *Constructionist learning* (pp. 121–8). Cambridge, MA: MIT Media Laboratory.
- Rheingold, H. (1985). *Tools for thought*. New York: Simon & Schuster.
- (1991). *Virtual realities*. San Francisco: Whole Earth Press.
- Rogoff, B. (1990). *Apprenticeship in thinking: Cognitive development in social context*. New York: Oxford University Press.
- Rubin, A., Bruce, B., Conant, F., DuMouchel, W., Goodman, B., Horwitz, P., Lee, A., Mesard, W., Pringle, L., Rosebery, A., Snyder, R., Tenney, Y., & Warren, B. (1990). *ELASTIC: Environments for learning abstract statistical thinking (annual report)* (BBN Rep. No. 7282). Cambridge, MA: Bolt Beranek & Newman.
- Rubin, A., Rosebery, A., Bruce, B., & DuMouchel, W. (1988). *Getting an early start: Using graphics to teach statistical concepts in high school*. Alexandria, VA: American Statistical Association.
- Russell, S. J., & Corwin, R. B. (1990). *Used numbers: Real data in the classroom – The shape of the data*. Palo Alto, CA: Seymour Publications.
- Salomon, G., Perkins, D. N., & Globerson, T. (1991). Partners in cognition: Extending human intelligence with intelligent technologies. *Educational Researcher*, 20 (3), 2–9.
- Saxe, G. B. (1988). Candy selling and math learning. *Educational Researcher*, 17 (6), 14–21.
- (1990). *Culture and cognitive development: Studies in mathematical understanding*. Hillsdale, NJ: Erlbaum.
- Schoenfeld, A. (1985). *Mathematical problem solving*. New York: Academic Press.
- Schön, D. (1983). *The reflective practitioner*. New York: Basic Books.
- Scribner, S. (1985). Knowledge at work. *Anthropology and Education Quarterly*, 16, 199–205.
- (1986). Thinking in action: Some characteristics of practical thought. In R. J. Sternberg & R. K. Wagner (Eds.), *Practical intelligence: Nature and origins of competence in the everyday world* (pp. 13–30). Cambridge University Press.
- Simon, H. (1981). *The sciences of the artificial* (2d ed.). Cambridge, MA: MIT Press.
- Suchman, L. A. (1987). *Plans and situated actions: The problem of human-machine communication*. Cambridge University Press.

- Thornton, R. K., & Sokoloff, D. S. (1990). Learning motion concepts using real-time microcomputer-based laboratory tools. *American Journal of Physics*, 58, 858–67 (app. B).
- Tinker, R. (1992). *Thinking about science*. Cambridge, MA: Technical Education Research Center.
- Vygotsky, L. S. (1978). *Mind in society: The development of the higher psychological processes*. Cambridge, MA: Harvard University Press. (Originally published 1930.)
- Wartofsky, M. (1979). *Models: Representation and the scientific understanding*. Boston: Reidel.
- (1983). The child's construction of the world and the world's construction of the child: From historical epistemology to historical psychology. In F. S. Kessel & A. W. Siegel (Eds.), *The child and other cultural inventions* (pp. 188–215). New York: Praeger.
- Wenger, E. (1991). *Toward a theory of cultural transparency: Elements of a social discourse of the visible and the invisible*. Unpublished doctoral dissertation, University of California, Irvine.
- Wertsch, J. V. (1985). *Vygotsky and the social formation of mind*. Cambridge, MA: Harvard University Press.
- (1991). *Voices of the mind*. Cambridge, MA: Harvard University Press.
- Wertsch, J. V., McNamee, G. D., McLane, J. B., & Budwig, N. A. (1980). The adult-child dyad as a problem-solving system. *Child Development*, 51, 1215–21.
- White, B. Y. (1988). *ThinkerTools: Causal models, conceptual change, and science education* (BBN Technical Rep. 6873). Cambridge, MA: Bolt Beranek & Newman.
- White, B. Y., & Horwitz, P. (1987). *ThinkerTools: Enabling children to understand physical laws* (BBN Technical Rep. 6470). Cambridge, MA: Bolt Beranek & Newman.
- Wilhelmson, R. B., Jewett, B. F., Shaw, C., Wicker, L. J., Arrott, M., Bushell, C. B., Bajuk, M., Thingvold, J., & Yost, J. B. (1990). A study of the evolution of a numerically modeled severe storm. *International Journal of Supercomputer Applications*, 4 (2), 20–36.
- Winograd, T., & Flores, F. (1987). *Understanding computers and cognition: A new foundation for design*. Reading, MA: Addison-Wesley.
- Zuboff, S. (1988). *In the age of the smart machine: The future of work and power*. New York: Basic Books.