The Evolving Science of Learning

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What is our most important science? Some might say physics, because it discloses the fundamental mechanisms of nature. Others might say genetics, because it seems on the verge of yielding enormous power to manipulate the biological world. But a case can also be made for what might be called "mind science"—the scientific study of human beings as thinking and learning organisms.

The lawyer for the defense would emphasize the logic of the matter. *Most fundamentally, we human beings are thinkers and learners.* Without thinking and learning, we would have little of what we now possess, including powerful questions that promise to extend our understanding and capabilities even further. To the degree that we fathom the nature of the mind and how to cultivate it, we have mastered the essence of the human condition. Imagine a world in which every school child, every business person, every politician, every parent, and indeed every teacher thought much better and learned much more than at present!

The lawyer for the prosecution might acknowledge the potential, but would certainly accentuate a cautionary fact: The scientific study of learning is today not as unified or powerful as physics or genetics. At the heart of a science of learning must lie an accurate conception of how the human mind actually works. Unfortunately, contemporary psychology is home to multiple views of the mind. Educators who are determined to put learning science to work face a sampler of perspectives, some complementary, some in conflict, and some better suited to particular agendas than others.

Views of the mind over the past century fall broadly into the behaviorist view that dominated the first half of the century and the cognitive view that has dominated much of the second. Although treating the history of learning science in terms of this shift is tempting, the story is much more complicated. For example, contemporary cognitive science, a sprawling conglomerate of theories and stances, is much broader than behaviorism was. And recent developments in neuroscience are broadening the field even further, shedding new light on earlier findings by disclosing a physiological basis for thinking and learning.

Our focus in this chapter is only indirectly on the scientific study of thinking and learning. We are concerned here primarily with how various conceptions of the mind have influenced the practice of education, and how they may affect it in the future. We begin with behaviorism, then turn to cognitive science, leading to major themes influencing schools in recent decades: constructivism and human development, intelligence and the skills of thinking, and brain research. We conclude by discussing a few themes most likely to affect education in the decades to come.

BEHAVIORISM

SCENARIO 1

Dr. Bea Havior, principal of Rewards Elementary School, greets nine students who have been sent to her office to be honored for their achievements.

"Congratulations to each of you," she says warmly. "Your teachers have told me that you have earned a high score on our local test of one of the state standards of learning, demonstrating that you are prepared to take the state test for

your grade level in the spring. Here is a certificate honoring you for the hard work you have done. And as you know, if you earn a certificate like this for a the standards at your grade level, you will be invited to a pizza party we will holding the week before the state tests. So keep working, and our school wi be proud of you."

SCENARIO 2

At nearby Warnum High School, students listen to an announcement over the public address system about a new policy the board of education had adopted a few days earlier:

"Beginning immediately, students with more than three unexcused absences are to be suspended from school until they return with their parents for a meeting with the assistant principal. To be readmitted, they must compose and sign an agreement to attend school regularly and propose a plan for how they will avoid unauthorized absences."

As mentioned earlier, the study of psychology was dominated for the first half of the century by behaviorism, the idea that mental processes are invisible and therefore not subject to scientific investigation. What could be observed was outward behavior, so rather than speculating on internal causes, scientists focused on how organisms responded to various stimuli, with rats and pigeons as favored laboratory animals. Because learning was defined as changed behavior, research on learning was concerned with what produced measurable changes. Much of this research dealt with the effects of positive and negative reinforcement—rewards and punishments—on learning.

The influence of rewards and punishments can certainly explain a substantial portion of our actions, as it does those of other animals. For many centuries, rulers, employers, and parents recognized and exploited this trait before it became the object of scientific investigation. By studying the phenomenon systematically, behaviorist psychologists added to our understanding of human learning.

Behaviorists argue that organisms learn through classical and operant conditioning. Complex behaviors are built up through "shaping," starting with parts of or rough approximations of the target behavior and providing reinforcement in ways that gradually shape the pattern of behavior in the intended direction. Much learning in natural circumstances occurs because the environment shapes behavior in this way. Not only direct rewards like food but also indirect "tokens" of reward shape behavior through learned associations. Research has yielded a body of findings about when reinforcement is best administered (broadly, immediately is best) and what kinds of reinforcement are most effective (in the long run, positive is generally better than negative, which can cause the learning organism to withdraw or become unresponsive).

What B. F. Skinner (1974) called "behavioral science" has been harshly criticized and is currently disparaged by most educational leaders, but a significant virtue of behaviorism is its emphasis on human adaptability. Because behaviorists believe that people's actions and capabilities are largely the result of environmental influences, behaviorists' work is a powerful counter to those who believe, or act as though they believe, that learning ability is unalterable. Behaviorism is therefore a positive force for democratic schooling, which assumes that all students have potential.

We should perhaps clarify that a focus on behavior is not necessarily behaviorist. One can analyze behavior or set detailed goals for desired behavior without believing that the best or only way to attain them is through a regimen of reinforcement. Likewise, one can have a behaviorist view of learning without long lists of specific target behaviors. The two are allied historically, but are not the same thing.

Poor practices are sometimes mistakenly criticized as behaviorist even though they have nothing to do with behaviorist theory. Giving a lengthy lecture to a group of bored, uninvolved students is not good behaviorist practice. A well-designed behaviorist lesson requires thoughtful attention to introduction of tasks, timing and character of reinforcements, and many other factors.

Some innovations that attracted educators' attention at various times throughout the century were explicitly or at least partially behaviorist. In the 1930s, evaluator Ralph Tyler, who later became an influential curriculum theorist, urged teachers participating in the famous Eight-Year Study (Aiken, 1943) to specify objectives for what their students should be able to do. A quarter century later, school systems required teachers to use "action verbs" as they wrote thousands of behavioral objectives. An influential theme in elementary, secondary, and higher education has been mastery learning (Bloom, 1968), which is

at least partially behaviorist in its emphasis on creating the conditions under which students will learn successfully.

Some teacher education has a behaviorist flavor. To ensure that beginning teachers could demonstrate a defined set of professional skills, schools of education have sometimes developed elaborate programs of competency-based teacher education. The effective teaching research of the 1980s (Rosenshine, 1986) dealt with particular teacher behaviors—such as providing systematic feedback and corrections—found to be associated with high student test scores.

As illustrated by the scenarios at the beginning of this section, some practices considered fundamental to learning are partly behaviorist in their assumptions. Teachers of younger children use praise and symbolic rewards, such as stickers and stars, to positively reinforce behaviors they want to encourage. Schools also rely on various punishments to shape student conduct and maintain order. Grades given to assignments and overall coursework function as positive or negative reinforcements. From a behaviorist standpoint, such reinforcements are most effective when students understand not only *that* they did right or wrong but also *what* they did right or wrong, and what they should do to improve. Instructional settings often fail to provide this information.

Behaviorism may be somewhat unfashionable, but it continues to influence educational practice. Although some applications are undoubtedly simplistic, distorted, or even harmful (Kohn, 1993), educators cannot avoid behaviorism entirely. They must to some degree view behaviors as indicators of students' intentions and wishes, and they will always find reinforcement an important tool for directing attention and effort in some directions rather than others. Results from behaviorist research can guide their work.

ENTER COGNITIVE SCIENCE

SCENARIO 1

Mr. Explicit is teaching his middle school science students about torque and balances. He shows them a balance scale with pegs on each side and different numbers of rings on the pegs.

Rather than saying just, "What do you think will happen?" he says, "Three weights on the third peg versus two weights on the fourth peg; what do you think will happen?" He also gives each student an external memory aid: a printed diagram of the problem. When students develop a hypothesis about a possible relationship between the weights and distances, he asks them to check the hypothesis using data from previous problems they have compiled on previous diagrams (Bruer, 1993, p. 48).

SCENARIO 2

Students in a reading class sit in groups of three to five. In an activity known as "reciprocal teaching" (Palincsar, Ransom, & Derber, 1988), one student at a time acts as teacher. As others in the group follow along, Anita reads aloud a paragraph from a story set in a Native American village in 1820. When she finishes reading, she briefly summarizes what the paragraph said and asks the other students a question about it. Satisfied with the answers, she tells one thing she isn't completely clear about and makes a prediction about what might happen next. Then another student reads the next paragraph and does the same.

In the years following World War II, psychologists began turning away from behaviorism to embrace a broader view eventually characterized as "cognitive science." Behaviorism had captured the field of psychology because it replaced unproductive introspection with quantifiable scientific procedures. Unfortunately, behaviorists tended to overstate their ability to fully explain all aspects of human thought and behavior. So when cognitivists made referring to internal mental processes academically respectable again, mind scientists regarded the renewed interest as a fresh opportunity.

A development often cited as particularly damaging to behaviorism was Chomsky's (1980) insight that rule-governed language—children's *ability to construct* linguistic structures they had never heard before—could only be explained by the existence of inherent mental and neurological structures. Behaviorists had assumed that language mastery was entirely the product of stimulus-response learning mechanisms. Plotkin (1998) explains that behaviorism did not permit

> Causal explanations if they did not lie within the limits of ordinary everyday experience. Scientifically this was an extraordinarily bankrupting stance. Cognitivism rescued psychology from this crippling narrow vision. It liberated psychologists conceptually and allowed causal powers to be relocated in the mind and brain, only a very [illegible]rt of whose workings are visible (p. 33).

Many educators welcomed the shift to a cognitive orientation because it meant that consideration of mental activity was no longer ruled out as unscientific. Teachers are, after all, concerned with students' thinking. They want students to understand and appreciate, and the effort to translate these aims into desired behaviors can be cumbersome at best. Yet cognitive science is still science, so its investigation of the mind goes beyond naive terms and concepts used in everyday conversation, like "idea" or "hunch."

Cognitive science has many branches and variations, and no simple description applies to them all. Obviously, the central theme is cognition, the process of knowing. Early research focused primarily on information processing, especially pattern recognition, memory, and problem solving. The mind was considered a rule-governed computational device. A scientist's task was to identify the specific rules by which the mind manipulates symbols to arrive at results. Over time, cognitive scientists gradually expanded their attention to include a remarkable array of human activities: the formation of judgments, decision making, creativity, critical thinking, and even the emotions.

For much of this work, the computer and information processing remained central metaphors. That the evolution of cognitive science paralleled the development of electronic computers is no coincidence, because cognitivists often emphasized similarities between the two. Concerned with information-processing functions, leading cognitive scientists described themselves as "functionalists." Francis Crick, the Nobel prize-winning scientist who collaborated in discovering the molecular structure of DNA, has observed that

> Just as it is not necessary to know about the actual wiring of a computer when writing programs for it, so a functionalist investigates the information processed by the brain, and the computational processes the brain performs on this information, without considering the neurological implementation of these processes (Crick, 1994, p. 18).

Crick's charge that functionalists have ignored the physiological basis for the processes they studied may be unfair, because until recently scientists had *few ways* to investigate the brain directly. As we show later, however, neuroscientists like Crick now insist that mental ctivity cannot be fully understood without reference to structure and peration of the brain itself.

Even so, cognitive scientists have profoundly influenced how ıformed professionals view learning (Bransford, Brown, & Cocking,)99). They have produced an extensive literature on cognition and a ide range of potentially useful programs and practices, although as ɿppens in almost all initiatives of educational change, most of these 'forts have seen only occasional use, generally in more progressive :ttings.

We discuss cognitive science from two points of view. First, we ıow how the cognitive orientation has affected educators' understand-:g of the learning process and therefore influenced how teachers teach. .ıen we consider how new views of learners' capabilities have contrib-:ed to attempts to improve students' intelligence and thinking skills.

Constructivism and Human Development

CENARIO 1

.r. N. Ductive asks his chemistry students to work in small groups with a list 95 book titles, each with a classification name and a number. They are to range the books on a seven-shelf bookcase with space for 32 books per ıelf, according to a set of rules. When all groups have finished, with several fferent results, he reintroduces the task as a metaphor for the periodic table elements (Brooks & Brooks, 1993, pp. 50–53).

CENARIO 2

:udents are working in groups to prepare presentations about the American əvolution, but when asked whether he's beginning to shape a plan for his part, ɪremy says, "Not really." Mr. Meta has him read a passage aloud and asks him hat is most important. Jeremy chooses the words "ammunition" and "mili-ry stores" because, he explains, "I like guns and stuff."

'ou're thinking about how the text reminds you of your own life," says Mr. leta. "That's one way to decide what's important. Let's break this passage ɔwn a little to make it easier to decide what's important. Great readers are inking all the time as they read, 'What's most important?' I'm going to read at sentence you just pointed to. You listen, and I want you to tell me what ıu think is most important in that one sentence, Okay?" (Keene & Zimmer-ann, 1997, pp. 83–86).

The Mind's Role in Constructivism

Part and parcel of the cognitive revolution is a theme called constructivism (see, for example, Duffy & Jonassen, 1992). Both a philosophical and psychological stance, constructivism argues that the human mind does not simply take in the world but makes it up in an active way. The creative role of the mind is obvious in contexts such as scientific inquiry and artistic endeavor, but constructivists believe that the constructive process also figures prominently even in such seemingly routine mental operations as perception and memory.

Much evidence demonstrates that both operations are highly constructive. When we form a perception of the room around us, a new acquaintance's personality, or an event we have witnessed, we do not simply register it like a camera. We engage in a complex act of information processing, combining the information our senses give us with a host of expectations to fill in the gaps, devising something much more like an interpretation than a snapshot. Likewise, remembering, far from replaying some mental tape recorder, works more like problem solving. It involves reconstructing a version of what happened from memory traces and a range of expectations.

The mind's pervasively constructive character is both bad news and good news for the effectiveness of cognition. On the down side, perception and memory, as well as more obviously interpretive activities, such as writing fiction, turn out to be highly susceptible to a range of mistaken presumptions and biases. On the up side, the mind's constructive character means that we can make sense of things with much less information than if we had to draw conclusions mostly from the data at hand.

Philips (1995) distinguishes three strands in constructivism: the active role of the thinker and learner, the creative role of the thinker and learner in making up knowledge, and the social construction of knowledge. Different theorists foreground various combinations and offer different pedagogical prescriptions. In the same spirit, Perkins (1992b) distinguishes between without-the-information-given (WIG) constructivism and beyond-the-information-given (BIG) constructivism. Ardent WIG constructivists argue that for real learning, students must virtually reconstruct knowledge for themselves, with appropriate support. BIG

:onstructivists believe that giving learners information directly is fine ınd often preferable; but to learn it, they must then apply it actively ınd creatively. Infighting among moderate and extreme schools of hought about what teaching in a constructivist way means inevitably veakens the momentum.

IOW CHILDREN'S THINKING DEVELOPS

Another theme closely allied with constructivism is that of human levelopment. The premise for a developmental view of mental maturaion came from observations that youngsters often had difficulties in hinking and understanding that went beyond simple lack of knowl-:dge. Certain kinds of reasoning, ways of using numbers, or manners)f appreciating another person's perspective seemed beyond young-;ters of certain ages, no matter how much explanation or practice they ·eceived. Perhaps such things depended on broad waves of develop-nent, which brought into place necessary cognitive equipment.

The most renowned advocate of this view was undoubtedly the ;wiss psychologist Jean Piaget (Inhelder & Piaget, 1958; Piaget, 1954). Vith his colleague Inhelder, Piaget proposed that development pro-:eeded through several stages of cognitive capability, culminating in what he termed "formal operations." Before children attained the ıighly general cognitive schemata underlying formal operations, they :ould not be expected to handle deductive reasoning or, among other things, manage scientific inquiry well. Early applications of Piaget's model led to curriculums that did not even attempt to engage young children in scientific reasoning, on the grounds that they were not up to it.

A number of studies conducted since Piaget's research program argue that Piaget's proposed stages are too broad. Development proceeds in a more modular way within different domains or kinds of thinking. Neo-Piagetians adopting this view have outlined more focused developmental tracks. For instance, Case (1992) argues that development travels along the tracks of several central conceptual structures, including understanding of quantity and of social matters such as intentionality.

Both the more modular view of development and a number of teaching exp[illegible] ts have shown that youngsters can manage various kinds of reasoning considerably earlier than had been thought. An early champion of this sort of flexibility was the seminal cognitive and developmental psychologist Jerome Bruner, who wrote in 1960 the well-known statement, "We begin with the hypothesis that any subject can be taught effectively in some intellectually honest form to any child at any state of development" (Bruner, 1973, p. 413).

At the most general level, constructivism and developmental science offer two guidelines for education: Cast the learner in an active, creative role rather than that of a passive receptacle; and take into account what the learner is ready for developmentally. Thus, in the opening scenarios, Mr. N. Ductive and Mr. Meta both insist that their students think things out rather than just give them the answers or even routine procedures with which to find the answers. From a developmental standpoint, activities like Mr. N. Ductive's rule-following classification task should work well for high school students but would need dramatic simplification for 3rd graders. Mr. Meta's rather generalized "think about what's important" focus, however, would work more or less as is across a wide range of grades and developmental levels, with Mr. Meta making on-the-fly adjustments in the sophistication of the discourse.

Although both constructivism and a developmental perspective have generated bold calls for pedagogical reform, the calls have generally been louder than the response. A good deal has happened to revise teaching practices and developmentally appropriate curriculums (see, for example, Bruer, 1993; Perkins, 1992a), but not nearly as much as champions would like to see. On the practical side, these agendas generate a variety of problems with classroom management, materials support, time required for covering the curriculum, teachers' stock of developmental knowledge, and the like. Moreover, different stances on both constructivism and human development have often confused teachers.

INTELLIGENCE AND THE SKILLS OF THINKING

SCENARIO 1

Ms. Ima Thinker has asked her elementary school students to meet in groups of three or four. She gives each group a collection of small tools often kitchens, such as can openers, vegetable peelers, and potato mashers. She asks them to group the items in a way that makes sense to them and think of an appropriate name for each group. Then, after returning everything to a common pile, they are to sort the items again in a different way, and again name the groups. Later Ms. Thinker explains that this is an exercise in classifying, and that next they will be classifying words rather than things. She gives each group a list of words and asks them to write the words on slips of paper and sort them. When the students report out various ways of classifying the words, she introduces the idea of "parts of speech."

SCENARIO 2

At Socrates Elementary School, students are involved in an animated discussion. After the class has read a story about two young friends who get angry with one another, Ms. Logic asks questions about friendship. "If a friend does something you don't like, is she still a friend?" Students express their ideas, with the teacher leading but not dominating the discussion. Her purpose is to encourage students to define terms precisely and to support their positions logically, but not to get them to arrive at any particular conclusion.

The prospects of improving human thinking and learning have long been recognized. The disciplined inquiries of Socrates and Plato, built on the discoveries of Greek rhetoric, pointed toward using the mind more rigorously. Aristotle extended the available tools with the logical forms of the syllogism. Church scholars such as Saint Augustine picked up on the power of systematic reasoning, and Francis Bacon in the early 1600s articulated basic principles of the scientific method.

The last half century has seen a groundswell of attention on directly cultivating thinking and learning. Cognitive science was partly responsible. Early studies of problem solving and memory disclosed that effectiveness was partly a matter of strategy. Some people managed their minds better than others. Why not, then, teach people good practices of problem solving, memorizing, and other sorts of thinking? The other wellspring was philosophy, a discipline that had long stood back to examine the process of thinking itself. Some philosophers concentrated on pre-university education, exploring what could be done to bring into the classroom some of the concepts and practices that had invigorated philosophical inquiry since the Greeks.

The most visible result of all these efforts is a variety of curricu-

cognitive abilities. Such materials have strikingly diverse approaches. Some focus on basic operations of classification and discrimination, emphasizing tasks like those that appear on IQ tests. The first scenario in this section and the first part of the Odyssey program (Adams, 1986; Herrnstein, Nickerson, Sanchez, & Swets, 1986) are examples of this focus. Other programs, such as Instrumental Enrichment, encourage students to develop more precise, systematic, and attentive processes of information intake, manipulation, and output (Feuerstein, 1980). Still others focus on familiar kinds of thinking, such as problem solving, decision making, and creativity, as in other parts of Odyssey or Edward de Bono's (1973–1975) CoRT program. Some are based on developmental psychology, for instance, the work of Piaget (Adey & Shayer, 1994). A few, notably Philosophy for Children, deal with classical matters, such as using syllogisms and clarifying the meaning of words, as in Scenario 2 (Lipman, Sharp, & Oscanyan, 1980). Recommended teaching methods range from assigning problem sets of open-ended thinking activities to leading Socratic conversations.

Although many educators are intrigued by the possibility of augmenting students' mental abilities, relatively few elementary and secondary schools have taken steps to incorporate published thinking skills programs into their official courses of study. Schools often find that making time for a substantial addition to already packed schedules is difficult. Recent years have probably seen even fewer applications than in the mid-1980s, in part because the adoption of state content standards has narrowed the scope of curriculums.

Another factor impeding advancement of the thinking skills movement has been the existence of theoretical controversies, such as disputes over the nature of human intelligence. A view common since the turn of the century is that intelligence is largely determined by genetic factors and not subject to much educational influence. As recently as 1994, Herrnstein and Murray advocated this position in the well-known book *The Bell Curve*. This discouraging stance certainly has not won the day. A number of serious challenges have been posed from the perspectives of multiple intelligences (e.g., Gardner, 1983; Sternberg, 1985) and various ways of cultivating intelligence (e.g., Baron, 1988; Perkins, 1995). Indeed, considerable evidence exists that intelligence can be enhanced to a useful, albeit limited, extent (Perkins, 1995;

Perkins & Grotzer, 1997). The very existence of the controversy, however, has made many educators wary of investing in efforts to enhance learners' thinking and learning.

Another such controversy arose from a different quarter. Some theorists challenged the idea that general cross-domain strategies of thinking and learning had much leverage. Instead, they believed that knowledge and understanding were profoundly "situated"—specific to various disciplines and areas of practice. Thinking could be taught, they contended, but it should be taught through the various disciplines in ways fine-tuned to their particular styles of problem solving and inquiry (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991). Undoubtedly, this view has a measure of truth, but strong counterarguments have been offered against extreme situated stances (e.g., Anderson, Reder, & Simon, 1996). The truth likely lies somewhere in between, with room for some strategies of thinking and learning, but suitably adapted to particular contexts (compare to Perkins & Salomon, 1989). Again, controversy has discouraged some educators.

Partly as a consequence of the situated view and partly to dodge scheduling issues, perhaps the most common approach to the teaching of thinking and learning is "infusion," as it is sometimes called. Infusion means systematically incorporating thinking and instruction into subject matter classes. Besides stand-alone courses, some systematic approaches to infusion exist (e.g., Swartz & Parks, 1994; Tishman, Perkins, & Jay, 1995; Marzano, Pickering, et al., 1997). Teachers' efforts are sometimes made easier by subject matter textbooks that call for students to classify information, compare concepts, or use other such skills, a practice that has become more common as the importance of thinking skills has become more widely accepted.

Integrating content and thinking is certainly desirable, but this approach brings problems of its own. Under pressure to cover content, teachers may find the thinking side of a curriculum giving way to the content side. Moreover, individual student efforts are difficult to monitor or coordinate. Some published intensive programs show considerable evidence of effectiveness, but we simply don't know the extent to which teachers of regular classes provide explicit teaching of thinking or, if provided, what such integrated instruction accomplishes.

As understanding of the human mind continues to grow, and as knowl[illegible] it reliable means of developing students' cognitive

capabilities continues to expand, educators will need to resolve the responsibility issue. Schools must determine how they propose to use this knowledge systematically to help all students sharpen their thinking and learning abilities.

Brain Research

Scenario 1

Students in Metro Middle School are practicing self-control in their social and emotional learning class. Two volunteers agree to role-play a typical situation. Pretending to be walking in the school hallway, one bumps against the other. The bumped student, who would ordinarily feel he must defend his honor by hitting back, uses the "red light, yellow light, green light" strategy (Elias et al. 1997, p. 29).

Speaking aloud in this case, he says, "Red light: Don't do anything yet. Yellow light: Think of things you might do and what might happen if you did them. Green light: Decide what is best and do it." He decides the bump probably wasn't intentional, or maybe it was just in fun, so he will ignore it for now.

Scenario 2

A high school biology class has begun to study DNA. At the beginning of class, Ms. Rhea Member asks students to jot down notes about what happened yesterday and then meet with a partner to discuss what they remembered. As she provides more information about DNA, she pauses occasionally to have partners explain to one another what they've just heard. A few minutes before the class is to end, she asks students to represent some aspect of what they've learned by making a diagram or sketch in their notebooks. She tells them that tomorrow she will give them some time to meet in learning teams to begin planning for a presentation they are to give next week, complete with visual aids. They are to portray knowledge of DNA in relation to a television program, well-known book, or song.

In the last decade, educators have begun to tap a comparatively new source of knowledge about the mind: neuroscience. Curious investigators have studied the physical brain for many years, of course, but only in the last few years have new noninvasive technologies, such as functional magnetic resonance imaging (fMRI), revealed exciting new information about workings of a normal, undamaged brain. Opinions about the immediate usefulness of these new findings vary greatly.

Some interpreters believe brain research provides support for particular approaches, such as real versus symbolic input (Hart, 1998), active processing of experience (Caine & Caine, 1997), enrichment in early childhood (Diamond & Hopson, 1998), and use of color and movement (Jensen, 1998).

Scientists themselves are generally more cautious. For example, at an invitational meeting of educators and brain researchers held under the auspices of the Education Commission of the States (1996), "the scientists urged the educators not to attempt to apply new research findings" (p. vi). John Bruer, a cognitive psychologist and president of the McDonnell Foundation, states flatly that "right now, brain science has little to offer educational practice or policy" (p. 14). Stephen Pinker (1997), director of the Center for Cognitive Neuroscience at the Massachusetts Institute of Technology, apparently agrees. In *How the Mind Works*, he writes,

> This book is about the brain, but I will not say much about neurons, hormones, and neurotransmitters. That is because the mind is not the brain but what the brain does. . . . My point is not that prodding brain tissue is irrelevant to understanding the mind, only that it is not enough. Psychology, the analysis of mental software, will have to burrow a considerable way into the mountain before meeting the neurobiologists tunneling through from the other side (pp. 24–26).

To make sense of the differing stances, educators perhaps need to understand the professional orientations of these authors. As explained earlier, cognitive science was born a quarter century before the recent proliferation of brain research. Just as behaviorism made headway by ignoring vague and unmeasurable concepts about the mind, cognitive science progressed by excluding some aspects of mentality that brain researchers are now able to study. At least, that's how it seems to neuroscientists. Francis Crick, quoted earlier as saying cognitivists were interested only in the software and not the hardware of the brain, commented,

> This attitude does not help when one wants to *discover* the workings of an immensely complicated apparatus like the brain. Why not look inside the black box and observe how its components behave? It is not sensible to tackle a very difficult problem with one hand tied behind one's back (p. 18)(emphasis in original).

Educators' purposes are different, of course. Their intent is not to discover the workings of the brain; they just want to help students learn by making use of what *has been discovered*. They must be cautious, because much about the brain remains unknown, and much current knowledge is highly tentative. Nevertheless, Crick is right about the folly of trying to understand the mind "with one hand tied behind one's back." If no other knowledge existed about teaching and learning, we could not derive pedagogy from brain research. But we do have insights from several sources—including cognitive science, educational research, and thoughtful professional experience. Combined with this existing knowledge, brain research has the potential to enrich educational practice.

A good example of how neuroscience can help solve learning problems is *Fast ForWord*, created by researchers Paula Tallal and Michael Merzenich (1997). They developed the program in response to Tallal's findings that some children have trouble learning to read because they do not process speech sounds fast enough to hear phonemic differences. Based on Merzenich's research exploring the brain's plasticity, the program uses computer games incorporating artificially extended speech. Playing the games, children first learn to recognize sounds and then gradually increase their processing speed until they can hear the sounds in normal speech.

Knowledge about the human brain's functioning is far too extensive to be summarized in a paragraph or two. But here are a few generalizations that, in combination with other knowledge, suggest numerous implications about teaching and learning:

• The product of hundreds of millions of years of evolution, the brain is not a general-purpose, problem-solving device but rather a collection of systems (e.g., the ability to sing and the ability to count), each designed to serve a specific purpose (Restak, 1994). All human brains are alike in some ways, but each is also different. The general capabilities that make us human, such as language, have a neuronal substrate, so they are not developed solely through experience (Plotkin, 1998). The organization of each individual brain, however, changes in direct response to experience (Diamond & Hopson, 1998).

• The brain is incredibly complex, processing many inputs simultaneously and in multiple ways (Edelman, 1992). Emotions—which are probably related to chemical neurotransmitters found throughout the body as well as in the brain (Pert, 1997)—play an important role in determining what we pay attention to, how we make personal decisions, and what we remember (Damasio, 1994). Memories that are recalled from time to time are retained because the connections among neurons are repeatedly strengthened. For the same reason, tasks done frequently (like driving a car or tying shoestrings) require less conscious attention and less brain energy (Calvin, 1996). Memories are not stored whole but are reconstructed by recombining aspects of an original experience, so experiences most likely to be remembered are those "that are targets of elaborative encoding processes" (Schacter, 1996, p. 56).

• Each brain attempts to make sense of the input it constantly receives by matching incoming sensations with related information stored from previous experiences. This process gives each individual the illusion of coherence and consistency, even though memories are highly unreliable, and individuals' interpretations of reality often differ dramatically (Gazzaniga, 1998).

Many educators will find in these statements confirmation of, and possibly new insights into, what they already know about human learning. In general, the findings help explain why students learn best from purposeful, meaningful experiences that engage their imaginations and arouse their emotions. In Scenario 1 at the beginning of this section, Ms. Rhea Member uses numerous techniques to encourage students to process information about DNA in the belief that the more extensively the information is encoded, the easier it will be to retrieve.

Teachers have also found that exercises like "red light, green light" described in the second scenario can help students learn to restrain emotional impulses that might otherwise "hijack" their brains. Researchers think the reason emotions have such power is that they were needed to survive in the past, as to a lesser degree they still are.

THE FUTURE OF A SCIENCE OF LEARNING

Full recognition of emotions—their role and relationship to other mental functions—is, in fact, one aspect of the more inclusive science of the mind th dvocates now believe is evolving (LeDoux, 1996). This

new, all-encompassing discipline, while drawing on knowledge from many sources, will be firmly anchored in the study of the physical brain and related neural systems. Although that focus may seem obvious to some, it is not yet obvious to many of today's academics and was certainly not assumed by scholars in the past. Most systematic investigation of the mind was and still is conducted without reference to the brain (and the rest of the body) for good reason: Advanced tools for studying the normal, living brain have only recently been invented.

But keeping the mind and brain apart is no longer necessary. Damasio (1994) refers to this mistaken dualism as "Descartes' Error," complaining that "the Cartesian idea of a disembodied mind" nevertheless remains influential (p. 250). By contrast, neuroscientists take a position more like that of Crick (1994), who declares in *The Astonishing Hypothesis* that each of us is "in fact no more than the behavior of a vast assembly of nerve cells and their associated molecules" (p. 3). Although Crick casts this proposition as a hypothesis to be tested rather than an established fact, he plainly believes it himself. And though, as Crick acknowledges, his doctrine is "alien to the ideas of most people alive today" (p. 3), some version of it will undoubtedly be more widely accepted eventually.

Given the directions that the study of the mind and brain is headed, we are probably safe in making this prediction: The field of study now known as cognitive science will become even more diverse, paying more attention to the study of topics such as emotions and consciousness that previously have been less central, and assimilating insights from behaviorism. This expanded field, which may be known as mind science, and which we are calling the science of learning, w specifically include all aspects of neuroscience, meaning investigati of the physical brain and related biology. The current competition between some cognitive psychologists and some proponents of brain research will gradually change to one of collaboration. Behaviorism, now in partial eclipse among educational theorists, will be reexamined for a range of insights about learning.

What else might we expect for education's future? As other authors in this yearbook have noted, predicting future developments is a highly unreliable undertaking. Nevertheless, by projecting from current trends, we can propose several generalizations that seem likely to become reality:

• *The quantity and quality of brain research, which has multiplied enormously in the past decade, will continue to increase.* With the steady improvement in technological means of conducting brain research, the number of neuroscientists and the topics they investigate is growing larger year by year. Eventually (perhaps 25 to 50 years), we will have a much more complete understanding of brain functioning. This information, along with knowledge from other branches of mind science, will have substantial implications for education. Specifically, research will reveal the origins of, and develop new responses to, variations in mental functioning, including some that are now considered disabilities. Research will add to our understanding of the abilities we call intelligences, including ways education can enhance them. It will also produce more detailed information about the workings of neurotransmitters and other communication mechanisms in the brain and body, thereby shedding light on such phenomena as emotions, memory, and imagination. Information of this sort quite likely will lead to expanded use of drugs capable of modifying natural processes, such as heightening memory.

• *Over time, research and evolving practice will untangle controversies that have blocked systematic application of learning science to education.* An example of this process is the controversy concerning phonics versus whole language, which has troubled the teaching of reading for decades. At this point, the debate appears largely resolved in a kind of synthesis that recognizes the important place of phonics but incorporates many whole language practices. Similarly, controversies such as whether intelligence can be enhanced or whether understanding is almost entirely discipline-specific are gradually working their way toward resolutions that seem likely to have the character of syntheses rather than stark victories.

• *Knowledge about learning will be a fundamental part of every educator's professional preparation, as well as every student's education.* As knowledge about the mind continues to grow, applications of this knowledge to education will become ever more apparent. Educators will be expected to be informed about, and to use, practices in accord with these findings.

Much of what is known about learning will also be taught directly to students in elementary and secondary schools. Few subjects could

possibly be more important than understanding oneself and others and improving the ability to manage one's own thinking and learning.

• *Applications of information technology will continue to evolve, with digital devices proliferating, many of them small, specialized, and inexpensive—designed to extend human capabilities or compensate for limits of the natural mind.* With extensive networking of such devices, it will become more difficult to differentiate between mental abilities of an unaided individual and capabilities of people linked to other humans and to machines. In recent years, parents and educators have often disputed whether children should use calculators before they have learned computation "by hand" or whether they should be able to write compositions on word processing programs equipped with spell checkers. Future educators will wrestle with similar questions involving newly created electronic aids, including speech recognition word processors.

• *The need for instruction in thinking skills will continue to grow to help public school students from families with limited means perform well in school.* For complex economic, social, and political reasons, the proportion of children living in undesirable conditions has been increasing in developed countries, especially the United States. Some of these children are from indigenous families with a history of neglect and impoverishment; others are part of the steady flow of immigrants out of underdeveloped countries. With economic and political unrest throughout the world, and the availability of modern transportation, this trend will undoubtedly continue, bringing even more children with different languages and traditions to public schools. Many of these children will be from families with rural backgrounds that are not equipped to provide the middle-class surroundings that contribute to school success. Because these are the children most able to profit from programs specifically designed to develop intellectual skills, the need for such programs will continue to grow.

Some developments we foresee are outside educators' scope of influence. Mind science, including study of the brain, will surely proceed in the 21st century regardless of what happens in schools. But some of the things we foresee will not happen, at least not as readily, without initiative and support from educators themselves.

In today's political climate, educators are under great pressure to somehow bring all children to higher standards of performance. In the years ahead, the pressure is sure to grow even more intense. We can succeed in meeting this challenge only with improved understanding of the thinking and learning process itself. Accurate knowledge about the human mind is essential to an enlightened education profession.

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