
Psychology's Role in Mathematics and Science Education

Nora S. Newcombe
Nalini Ambady
Jacquelynne Eccles
Louis Gomez
David Klahr
Marcia Linn
Kevin Miller
Kelly Mix

Temple University
Tufts University
University of Michigan
University of Pittsburgh
Carnegie Mellon University
University of California, Berkeley
University of Michigan
Michigan State University

Improving mathematics and science education in the United States has been a matter of national concern for over half a century. Psychology has a vital role to play in this enterprise. In this article, the authors review the kinds of contributions that psychology can make in four areas: (a) early understanding of mathematics, (b) understanding of science, (c) social and motivational aspects of involvement in mathematics and science, and (d) assessment of learning in mathematics and science. They also examine challenges to psychology's playing a central and constructive role and make recommendations for overcoming those challenges.

Keywords: psychology, mathematics, science, education, assessment, motivation

Ever since the Sputnik flight over half a century ago, there has been continuing concern about improving math and science education in the United States. Will America have enough skilled and creative scientists and engineers to keep it competitive in an increasingly technology-based world? Can it educate a general population that can comprehend and contribute to the crucial social, political, and economic issues raised by those scientific and technological advances? There has been some progress (see <http://www.nas.edu/sputnik/bybee4.htm> for reflections on what was learned in the first 40 years after Sputnik), but nevertheless advances have been slower than many would like. International comparisons suggest that the United States still lags behind many other countries in math and science, consistently scoring around the middle of the pack. For example, the Trends in International Mathematics and Science Study (TIMSS) found little measurable change in the performance of American fourth and eighth graders between 1995 and 2003 (see <http://nces.ed.gov/timss/>). Recent data from assessments conducted by the Organization for Economic Cooperation and Development's Program for International Student Assessment indicate no change in this situation between 2003 and 2006 (see <http://www.pisa.oecd.org/dataoecd/16/28/39722597.pdf>). National concern about these trends (or the lack of

trends) was crystallized in a National Academy of Sciences report titled *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Future* (National Academy of Sciences, National Academy of Engineering, and Institute of Medicine, 2005). In addition, there have been an impressive number of high-level reports on various aspects of this problem (summarized in Table 1).

In this article, we show how advances in psychological research in fields such as cognitive psychology, developmental psychology, cognitive science, and the emerging learning sciences or "science of learning" (White, Frishkoff, & Bullock, 2007) offer new opportunities to address these continuing questions. We present some examples of findings from recent research in four areas: early mathematics understanding; science understanding; social and motivational aspects of involvement in science, technology, engineering and mathematics (STEM); and assessment of STEM learning. Findings such as the ones we discuss give grounds for optimism about psychology's potential role in addressing the "gathering storm." However, there are also challenges to using these insights. In each section, we make recommendations regarding how to

Nora S. Newcombe, Department of Psychology, Temple University; Nalini Ambady, Department of Psychology, Tufts University; Jacquelynne Eccles and Kevin Miller, Department of Psychology, University of Michigan; Louis Gomez, School of Education, University of Pittsburgh; David Klahr, Department of Psychology, Carnegie Mellon University; Marcia Linn, Graduate School of Education, University of California, Berkeley; and Kelly Mix, Department of Counseling, Educational Psychology, and Special Education, Michigan State University.

This article is based on the work of a joint American Psychological Association (APA)/Society for Research in Child Development (SRCD) Presidential Task Force on Mathematics and Science Education convened by APA President Sharon Stephens Brehm and SRCD President Aletha Huston during 2007 and chaired by Nora S. Newcombe.

We thank Rena Subotnik, Ashley Edmiston, and Maya Bassford of APA's Education Directorate for their support and advice and John Hagen for attending the initial meeting.

Correspondence concerning this article should be addressed to Nora S. Newcombe, Department of Psychology, Temple University, 1701 North 13th Street, Room 318, Philadelphia, PA 19122-6085. E-mail: newcombe@temple.edu

maximize psychology's contribution to educational change. We call for collaborative research that brings together investigators with expertise in psychology, STEM education, STEM disciplines, and related fields to work actively and cooperatively to improve STEM education. We encourage research that fits in Pasteur's Quadrant (Stokes, 1997), that is, basic research that is also use-inspired. This kind of research has the potential both to enhance our understanding of basic psychological processes and to substantially improve STEM education, but the connections between psychological data and educational practice have often been difficult to forge. This is unfortunate, not only because psychological research has the potential to enrich and ground educational practice but also because educational practice has the potential to enrich and ground psychological research.

Early Understanding of Mathematics

When children arrive at kindergarten, they bring along a range of concepts based on informal experiences. These experiences accrue throughout childhood and likely provide the grounding for the acquisition of increasingly abstract symbols (Lakoff & Nunez, 2000). Psychological research has amassed much information about this informal knowledge as well as about the mechanisms that likely move children from one level of understanding to another (National Mathematics Advisory Panel, 2008). In this section, we look at three examples of the fruits of psychological research and consider their relation to educational practice.

First, consider what we know about preschoolers' understanding of quantitative transformations (e.g., addition and subtraction). This knowledge has been tested in very young children using ingenious, nonverbal tasks. In one study, Huttenlocher, Jordan, and Levine (1994) had children first watch as objects were successively hidden or removed from a hidden set and then indicate the resulting number by constructing an equivalent set. Other researchers have presented similar problems and then measured whether children reach into the hiding place to retrieve all of the items (Feigenson & Carey, 2003; Van de Walle, Carey, & Prevor, 2000). Children can complete such tasks early in development—performing above chance for very small set sizes in late toddlerhood.

One general implication of these findings is that teachers should expect children to have this informal knowledge when they enter school. However, further research is needed to make more specific connections to educational practice. For example, does nonverbal calculation ability predict later mathematical achievement? Perhaps children who enter school without this ability are slower to learn symbolic calculation procedures. If so, are there instructional interventions preschool teachers could use to close the achievement gap early on? Without targeted research, it is not clear what these interventions might be. Furthermore, in the cases where promising interventions for early childhood mathematics have emerged from small-scale psychological experiments, it is unclear whether they merit national implementation because they have not been tested in

large and diverse populations (e.g., low socioeconomic status (SES) as well as middle class) (National Mathematics Advisory Panel, 2008).

A second example comes from research on fraction concepts. Children typically have great difficulty learning fractions in school—starting in the early elementary grades and persisting into high school (Behr, Lesh, Post, & Silver, 1983; National Mathematics Advisory Panel, 2008). However, there is reason to think that this difficulty does not stem from failure to comprehend part-whole relations because children seem to understand these relations in informal tasks (e.g., Frydman & Bryant, 1988; Goswami, 1989; Paik & Mix, 2008). To illustrate, first- and second grade children readily matched fractional amounts of food (e.g., 1/4 of a watermelon = 1/4 of a banana), even though they failed similar verbal tasks (Paik & Mix, 2008). Mack (1993, 2000, 2001) described several case studies in which she posed fraction problems to elementary school children. Though the children initially struggled with these problems, Mack showed that when they were reminded of related informal experiences, such as dividing up a pizza, they easily determined the solutions. In fact, very few such reminders were needed to achieve dramatic results.

This finding points the way toward a powerful teaching tool for fractions, but it does not go far enough. For teachers to implement this idea on a larger scale, they would need to know whether reminders work in larger groups of children and with children from a range of socioeconomic backgrounds (National Mathematics Advisory Panel, 2008). Perhaps individual children need to be reminded of the specific experiences that matter to them. Alternatively, there may be a way to sequence fraction instruction for large groups that incorporates informal experiences more generally yet still engages most students. The answers to such questions are likely rooted in basic research on analogical transfer and reminders (e.g., Gentner & Toupin, 1986; Gick & Holyoak, 1983), but this may not be obvious to educators and to those who investigate educational practice. Psychologists have to play a role in bringing this information to the educational sphere and confirming that what they have observed in small-scale laboratory research translates into the classroom.

A third example of research in early mathematical development pertains to learning to coordinate various dimensions of quantity and understand their interactions. This question was a central aspect of Piaget's research on conservation. For example, he found that when young children were asked to judge the equivalence of two containers of liquid, they tended to overemphasize the height of the liquid and ignore its width. He argued that this mistake reflected an inability to maintain and coordinate attention toward two dimensions simultaneously—a logical capacity deemed necessary for higher level thought. Indeed, the inability to coordinate multiple dimensions of quantity may underlie a number of stumbling blocks in later mathematical reasoning. For instance, children as old as 7 years have trouble understanding that when the same amount of food is divided among more recipients, the sizes of the portions decrease (Correa, Nunes, & Bryant, 1998;

Table 1**Reports Addressing the Need for Improved Math and Science Education in the United States**

Report	Description
	Overarching reports:
<i>How People Learn: Brain, Mind, Experience and School</i> (National Research Council, 2000)	Focuses on current research on learning necessary for deep understanding, effective teaching, and supportive environments. Six key topics regarding understanding and five regarding teaching and supportive environments are discussed.
<i>Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Future</i> (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine, 2005)	Makes recommendations on how America can maintain its position in the fields of science and technology. It states that revitalizing mathematics and science education from kindergarten through 12th grade is essential, along with finding and keeping scientists and engineers from both the United States and abroad.
<i>From Neurons to Neighborhoods: The Science of Early Childhood Development</i> (National Research Council & Institute of Medicine, 2000)	Closely examines variables that affect very young children during development.
<i>Eager To Learn: Educating Our Preschoolers</i> (National Research Council, 2001b)	Illustrates the way in which young children are presently being educated, using examples from the field of cognitive science as a framework. The book offers conclusions and recommendations for early childhood education.
<i>Engaging Schools: Fostering High School Students' Motivation to Learn</i> (National Research Council & Institute of Medicine, 2004)	Reviews current research on what shapes adolescents' school engagement and motivation to learn, including new findings on students' sense of belonging, and looks at ways these can be used to reform urban high schools. This book looks at various approaches to reform through different methods of instruction and assessment, adjustments in school size, vocational teaching, and other key areas.
	Mathematics education:
<i>Adding It Up: Helping Children Learn Mathematics</i> (National Research Council, 2001a)	Describes in detail variables associated with learning mathematics.
<i>Review and Appraisal of the Federal Investment in STEM Education Research</i> (National Science and Technology Council, 2006)	"This report presents the results of an analysis of the federal government's investment in learning and education research within the domains of science, technology, engineering and mathematics (STEM)" (p. 2). The National Science and Technology Council's Education and Workforce Development Subcommittee created a STEM task force whose goals were to review the current federal investment in research in learning and education for Grades K–20, as well as to provide recommendations for strengthening the federal education research portfolio to improve "STEM learning and educational practices in the long run" (p. 2).
<i>Foundations for Success: The Final Report of the National Mathematics Advisory Panel</i> (National Mathematics Advisory Panel, 2008)	The National Mathematics Advisory Panel was created by President Bush to advise the President and the Secretary of Education on the best use of scientifically based research on the teaching and learning of mathematics, with a focus on algebra. Five task groups and three subcommittees were created; their evidence guidelines and initial findings are outlined in this report.
	Science education:
<i>Learning to Think Spatially: GIS as a Support System in the K–12 Curriculum</i> (National Research Council, 2006b)	Spatial thinking is a cognitive skill that can be used in everyday life, the workplace, and science to structure problems, find answers, and express solutions using the properties of space. It can be learned and taught formally to students with appropriately designed tools, technologies, and curricula. This report explains the nature and functions of spatial thinking and shows how spatial thinking can be supported across the K–12 curriculum through the development of appropriate support systems.

Table 1 (continued)

Report	Description
<i>Taking Science to School: Learning and Teaching Science in Grades K–8</i> (National Research Council, 2007)	What is science for a child? How do children learn about science and how to do science? Drawing on a vast array of work from neuroscience to classroom observation, <i>Taking Science to School</i> provides a comprehensive picture of what is known about teaching and learning science from kindergarten through eighth grade. By looking at a broad range of questions, this book provides a basic foundation for guiding science teaching and supporting students in their learning.
<i>Ready, Set, Science! Putting Research to Work in K–8 Science Classrooms</i> (Michaels, Shouse, & Schweingruber, 2007)	This volume is designed as a practitioner-oriented accompaniment to <i>Taking Science to School: Learning and Teaching Science in Grades K–8</i> . It summarizes the findings in <i>Taking Science to School</i> and then goes on to present detailed case studies of real classroom experiences that illustrate the complexities that science teachers grapple with every day: selecting and designing rigorous and engaging instructional tasks, managing classrooms, orchestrating productive discussions with culturally and linguistically diverse groups of students, and helping students make their thinking visible using a variety of representational tools. The aim is to make the implications of research clear, accessible, and stimulating for a broad range of science educators.
<i>America’s Lab Report: Investigations in High School Science</i> (National Research Council, 2006a)	Laboratory experiences as a part of most U.S. high school science curricula have been taken for granted for decades, but they have rarely been carefully examined. What do they contribute to science learning? What can they contribute to science learning? What is the current status of labs in our nation’s high schools as a context for learning science?
<i>Knowing What Students Know: The Science and Design of Educational Assessment</i> (National Research Council, 2001c)	Assessment: At a time when traditional testing is subject to increasing criticism, research suggests that new, exciting approaches to assessment may be on the horizon. Advances in the sciences of how people learn and how to measure such learning offer the hope of developing new kinds of assessments—assessments that help students succeed in school by making as clear as possible the nature of their accomplishments and the progress of their learning. <i>Knowing What Students Know</i> essentially explains how expanding knowledge in the scientific fields of human learning and educational measurement can form the foundations of an improved approach to assessment. These advances suggest ways that the targets of assessment—what students know and how well they know it—as well as the methods used to make inferences about student learning can be made more valid and instructionally useful. Principles for designing and using these new kinds of assessments are presented, and examples are used to illustrate the principles. Implications for policy, practice, and research are also explored.
<i>High Stakes: Testing for Tracking, Promotion, and Graduation</i> (National Research Council, 1999)	Everyone is in favor of “high education standards” and “fair testing” of student achievement, but there is little agreement as to what these terms actually mean. <i>High Stakes</i> looks at how testing affects critical decisions for American students. As more and more tests are introduced into the country’s schools, it becomes increasingly important to know how those tests are used—and misused—in assessing children’s performance and achievements.

Miller, 1984; Sophian, Garyantes, & Chang, 1997). This inverse relationship underlies a whole class of mathematics concepts that are based on part–whole relations, including fractions, division, and proportions. Each of these concepts is notoriously difficult for children to learn in school.

Errors and misconceptions persist well into adolescence (Behr et al., 1983).

Psychological research on number and amount relations has the potential to explain why this is so. However, this connection may not be immediately apparent because

the tasks used in these experiments are about sharing, rather than the kinds of part-whole problems typically posed in school. Research that could directly link the two topics would help bridge this gap. For example, it would be desirable to know whether training on number and amount relations in sharing situations would lead to improvement on fraction comparison tasks, like those used in schools.

Each of our three examples offers both promise and frustration. There are data with clear implications for mathematics education, and yet further research is needed to answer questions vital to bridging the gap between theoretical understanding of basic cognitive processes and what classroom practices are best. What leads to these gaps and how can we bridge them? One obstacle is that although, as we noted earlier, any attempt to improve math and science education lies squarely in Pasteur's Quadrant (Stokes, 1997), psychologists and educators tend to come at this "engineering design" question from different perspectives and tend to parse the learning landscape in different ways. Some psychologists tend to focus on general processes and conceptual primitives related to learning and motivation that can be incorporated into a number of different structures. For example, they may study how children learn division, but the choice to study this problem is somewhat arbitrary: Division problems may be more a vehicle for studying part-whole reasoning than an end in themselves. In contrast, many educators tend to parse the landscape in terms of school subjects and instructional topics. In the educational literature, research on science concepts might not be linked to research on math concepts, whereas in the psychology literature, these topics are seen as sharing common learning mechanisms, including analogical reasoning, the influence of language on cognition, symbol grounding, and so forth. Moreover, with respect to broad approaches to different types of instructional procedures, these different perspectives give rise to long-standing and highly contentious debates, such as the recent exchanges about the theoretical and empirical basis of constructivist approaches to science and math instruction (Hmelo-Silver, Duncan, & Chinn, 2007; Kirschner, Sweller, & Clark, 2006; D. Kuhn, 2007; Schmidt, Loyens, van Gog, & Paas, 2007; Sweller, Kirschner, & Clark, 2007). In addition, psychology may become preoccupied with questions that seem not to have direct links to education at all (e.g., the innateness of concepts).

Psychologists can take several steps to bridge this kind of gap. For example, we could write and publish review papers that are targeted at the education audience, in which we spell out how seemingly disparate educational problems are united at a process level. Another step is for psychologists to familiarize themselves with the educational literature on problems that relate to the processes they study. A third step is to take their own research programs closer to addressing problems in school learning by demonstrating that specific process deficits can account for failure to learn certain material or that addressing these processing deficits will lead to improved school learning in a variety of topics.

In addition, we note that psychologists tend to prefer small-scale studies that isolate and closely examine various cognitive processes, whereas educators deal with large-

scale problems and need large-scale data. Educators would need to know, for example, what the best "down and dirty" way is to measure math readiness in massive groups of preschoolers. If I test 1,000 preschoolers, how many are likely to lack the math readiness skills identified in psychological research? What happens to these children in the long term—do these deficits predict achievement in later grades? Psychologists could assist in this effort by either replicating their findings in larger populations or partnering with educational researchers who routinely do so. In a few areas, we are beginning to see this idea come to fruition. For example, the Cognitive Tutors and other technology-linked instructional systems used by researchers at the Pittsburgh Science of Learning Center have now logged over 30,000 hours of student instruction time and over 6 million student-tutor interactions, producing data available for extremely thorough analysis of fine-grained learning paths.

The encouraging fact is that when researchers have managed to bridge the gap between psychology and mathematics education, their work has yielded some striking insights. For example, by looking at the contexts in which children acquire mathematics, recent work has uncovered the origins of individual differences in early mathematical competence. Klibanoff, Levine, Huttenlocher, Vasilyeva, and Hedges (2006) looked at the kinds of mathematical input children were exposed to in different preschools, finding huge differences by SES in the nature and amount of mathematical talk that preschool teachers produced. These differences in experience seem a plausible source for the large SES-related differences in mathematics achievement when children enter school, differences that are the best predictor of later school mathematics achievement (Duncan et al., 2007). Yet these SES-related differences are far from immutable. Ramani and Siegler (2008) found that substantial differences between children from low- and middle-income families on number line estimation tasks were eliminated after children were engaged for only one hour in playing simple board games that required counting. This study demonstrates how research bridging education and psychology not only reveals new insights about basic cognition but can also point the way toward an evidence-based intervention.

In summary, psychologists have a great deal to contribute to the improvement of mathematics learning. Although this may require them to adapt some of their common research practices, doing so will pay off in terms of both practical utility and a deeper scientific understanding of the nature of mathematical development.

Understanding Science

Science education faces a somewhat different set of challenges than mathematics education does. For one thing, there is much less agreement about what constitutes "core knowledge" in science than in mathematics, and there is, accordingly, less consensus about optimal sequencing of different scientific domains. For another, science educators aim to convey not only the *content* of science but also the *processes* whereby scientific knowledge is acquired, re-

fined, revised, extended, and disseminated, including modes of argumentation and the social and professional context of the scientific enterprise. Although these issues are clearly important for those choosing to become mathematicians, in science the issues are important even for those who seek only to understand the field and to make informed decisions about scientific issues. For example, in the normal mathematics curriculum, one is quite unlikely to hear questions of the type “Where did the method of long division come from?” or “How sure are we of the method of integration by parts in calculus?” whereas such questions about the source and certainty of many scientific hypotheses are considered to be part of a real appreciation of science.

The recent National Academy of Sciences volume *Taking Science to School* (National Research Council, 2007) identifies several aspects of science that are essential to convey to students (see also Lehrer & Schauble, 2006, for an extensive treatment of the different forms of scientific knowledge that children must acquire). Educators want students to gain three things: knowledge about the natural world, understanding of the process by which that knowledge is generated, and an appreciation of the social and participatory nature of science.

Beginning with knowledge about the natural world, we note that there is a vast, almost overwhelming, amount of such knowledge, ranging from the periodic table, to plate tectonics, to Newton’s laws, and so on. Indeed, some of the most difficult decisions in the creation of any science curriculum concern what to include, what to leave out, and what to teach first. Cogent arguments can be made for just about any sequence of domain coverage, and the inevitable result of the deliberations of those setting state science standards is an accumulation of topics based as much on advocacy as on sound psychological and pedagogical principles (Gross et al., 2005). The end result, as many have lamented, is a science curriculum that is a mile wide *and* a mile deep (Li & Klahr, 2006). One possible contribution that psychology can make to this difficult problem is to characterize the different domains in terms of their cognitive and motivational demands and to use our knowledge of developmental psychology to guide curriculum selection and sequencing.

In addition to *what* has been discovered, students need to know about *how* those discoveries were made. Psychological research has tended to focus on basic, domain-general cognitive processes including formal logic, heuristics, and problem-solving strategies that span a wide range of scientific methods. The pioneering work in this area includes that of Inhelder and Piaget (1958) on formal operations, studies by Bruner, Goodnow, and Austin (1956) on concept development, and investigations by Watson (1960, 1968) on hypothesis-testing strategies. More recent studies have focused on problem-solving strategies for coordinating theory and evidence (Klahr, 2000; D. Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; D. Kuhn & Park, 2005), mastering counterfactual reasoning (Leslie, 1987), distinguishing patterns of evidence that do and do not support a definitive conclusion (Amsel & Brock, 1996; Beck & Robinson, 2001; Fay & Klahr, 1996; Vellom &

Anderson, 1999), and understanding the logic of experimental design (Chen & Klahr, 1999; Tschirgi, 1980). These heuristics and skills are considered important targets for research and for education because they are assumed to reflect domain generality and transferability (D. Kuhn et al., 1995; Ruffman, Perner, Olson, & Doherty, 1993). Psychological research has also identified important parallels between historical and philosophical aspects of science (T. S. Kuhn, 1962) and the process of cognitive development (Carey, 1985; Koslowski, 1996). It has identified the ways in which domain-specific knowledge evolves: sometimes via the gradual elaboration of existing theories through the accretion of new facts and knowledge and at other times by the replacement of one theoretical framework by another. Research in this tradition (Carey, 1988, 1991; Chi, 1992; Linn & Hsi, 2000) places less emphasis on the mastery of domain-general logic, heuristics, or strategies and more on processes of conceptual or theory change.

Last, science involves culturally established norms of argumentation, disagreement, presentation standards, and shared goals of truth seeking. These may be quite distinct from everyday nonscientific discourse. The participatory nature of science learning highlights that science is a culture made up several subcultures that differ in large and small ways (Latour, 1999; Longino, 2002). Psychological research based on this perspective emphasizes the fact that individual scientists or groups of scientists are part of a wider social environment, inside and outside science, with which they are in constant communication and that has strongly shaped their knowledge, skills, resources, motives, and attitudes.

One of the challenges of science instruction is that rather than entering the science class as “empty vessels” into which knowledge can be “poured,” novice science learners bring to the science classroom an accumulated configuration of preconceptions about the natural world. Some of these are partially correct and easy to modify (Vosniadou & Brewer, 1994), whereas others are fundamentally at variance with the concepts to be acquired and require radical reconceptualization (Chi, 1992, 2005). In the former case, instruction based on analogical processes may be very effective (Clement, 1993), but in the latter case, much research remains to be done to determine how best to overcome such misconceptions.

Another factor that makes it hard to teach science is that the language of science is confusingly similar to everyday language but may mean something quite distinct. The literature suggests that adolescent science learners import everyday understanding of words into the science classroom in a way that can lead them down the garden path or confuse them in subtle ways that teachers fail to recognize. Psychologists who study words and language might be able to shed light on the conditions that cause everyday prior knowledge to be a source of confusion. In addition to these conceptual and linguistic challenges, science instruction must deal with a puzzling paradox in the nature of children’s acquisition of causal reasoning processes. On the one hand, there is evidence for surprisingly sophisticated causal reasoning in very young children

(Gopnik & Schulz, 2007), but on the other hand, there is evidence that even adults have great difficulty isolating causal factors in simple everyday contexts and that absent explicit instruction they have a difficult time designing empirical investigations that can minimize causal ambiguity.

One fundamental goal of science education, as stated in *Taking Science to School* (National Research Council, 2007), is that children should be able to “know, use, and interpret scientific explanations of the natural world” (p. 2). In addition, science education must clarify the distinction between what science is and is not. More specifically, it needs to convey what kinds of questions can be answered by scientific inquiry and what kinds cannot. For example, in the common “day at the pond” experience used in elementary science education, the following types of questions are grist for the scientist’s mill: “What makes the pond look green?” “Why is one kind of vegetation on this side, and another on the other side?” In contrast, it is important to delimit the scope of science from questions of meaning or social convention such as “Why are we here?” or “Why do we drive on the right?”

So, in summary, we know a lot about early scientific thinking. What don’t we know? An important issue is that our generalizations are based on specific topics, specific types and ages of students, and particular instructional strategies. However, to date, psychological research has explored only a small part of this overall space. We do not have an overarching and interconnected theory to address all of these phenomena in a systematic fashion or one that can suggest practical instructional strategies (pedagogy, materials, texts, sequencing, etc.) for a broad range of topics in the sciences (chemistry, physics, biology, etc.) and the wide range of ages over which science is taught in school.

Our suggestions for future research in this area are consistent with the broad set of recommendations made in the recently published Institute of Education Sciences practice guide *Organizing Instruction and Study to Improve Student Learning* (Pashler et al., 2007, p. 2):

1. Space learning over time.
2. Interleave worked example solutions with problem-solving exercises.
3. Combine graphics with verbal descriptions.
4. Connect and integrate abstract and concrete representations of concepts.
5. Use quizzing to promote learning.
6. Help students allocate study time efficiently.
7. Ask deep explanatory questions.

These recommendations are based on several decades of work in the learning sciences as applied to math and science education. Perhaps the most notable feature of this practice guide is that it indicates that the strength of the evidence supporting most of the recommendations is “low” to “moderate” in most cases, and “strong” in only a few (Pashler et al., 2007, p. 2). Clearly, much work remains to be done before psychologists can make suggestions to

science and math educators that are strongly supported by our research.

Social and Motivational Issues

Over the last 30 years, many psychologists have studied the motivational influences on learning and engagement in math and science. Much of this work began in the 1970s with a concern regarding the underparticipation of females in STEM courses in high school and college and the underrepresentation of females in STEM careers. Although there has been a major increase in the participation of women in various STEM college majors and professions, females and minorities are still underrepresented in some disciplines including mathematics, physics, chemistry, computer science, and engineering, especially at the higher levels such as full professorships (Hyde & Linn, 2006; National Science Foundation, 2008). In addition, overall, American students are underrepresented in STEM college majors compared with the proportions of students in those majors in other countries (National Science Foundation, 2008). One way to understand this situation is in terms of social and motivational issues.

Eccles, Barber, and Josefovicz (1999) proposed a comprehensive theoretical model of the motivational and social influences on students’ engagement and performance in mathematics. Drawing on the classic expectancy value theory of motivation, they linked achievement-related choices (such as the decision to take advanced math and science courses in high school, or the decision to seek training to enter a STEM field, or the willingness to engage fully in learning STEM material in primary and secondary school) to two sets of beliefs: the individual’s expectations for success (“Can I do the task?”) and the importance or value the individual attaches to the various options perceived by the individual as available (“Do I want to do the task?”). These beliefs are related to cultural norms, experiences, aptitudes, and those personal beliefs and attitudes that are commonly assumed to be associated with achievement-related activities (see Eccles, Wigfield, & Schiefele, 1998), including causal attributions, beliefs regarding the nature of intelligences, the input of parents, peers, and teachers, culturally based beliefs about both the nature of achievement domains and the “appropriateness” of participation, self-perceptions and self-concepts, perceptions of the task itself, and the processes and consequences associated with identity formation.

Beginning with the question “Can I do the task?” extensive work based on self-efficacy theory has documented the critical importance of confidence in one’s ability to master the material being taught in STEM classes for persistence and performance, particularly when one is faced with difficult material. Using both survey and intervention methods, many psychologists have demonstrated the power of increased confidence in one’s math ability for sustaining engagement and performance in STEM learning activities (Bandura, 1997; Pajares, 1996; Wigfield, Eccles, Schiefele, Roeser, & Davis-Kean, 2006). Much of the recent work has focused on the psychological and social forces underlying individual differences in the answer. One

major thrust in this area is grounded in Dweck's work on theories of intelligence along with the recent work in achievement goal theory. Dweck (1986, 2002) identified two different theories of intelligence that are likely to affect students' continuing engagement in STEM through their impact on individuals' confidence in their ability to master difficult STEM material. She proposed that entity theorists, who believe that intelligence is fixed, are likely to lose confidence in their ability to master math and science when faced with difficult problems and preliminary failure experiences. In contrast, incremental theorists, who believe that intelligence is malleable, are more likely to attribute learning difficulties to lack of experience and to continue to have confidence in their ability to master the material despite initial failures.

Advocates of achievement goal theory link individuals' theories of intelligence to more general motivational orientations (e.g., Anderman, Maehr, & Midgley, 1999; Midgley, 2002). These scholars argue that entity theorists tend to focus on performance goals (doing better than others and getting high grades), leading them to focus on relative ability, to avoid challenging situations unless they are certain of success, and to perform less well when challenged. In contrast, because incremental theorists focus more on learning/mastery and improvement and believe that failure is due to lack of knowledge rather than lack of "ability," they do well when challenged and persist despite initial difficulties. This line of reasoning has led to a large body of research studies focused on the differences in mastery/learning goals versus ability/performance goals. By and large, this work has shown that approaching STEM learning situations with learning/mastery goals leads to improved performance and greater persistence. For example, Grant and Dweck (2003) followed college students in an introductory chemistry course and found that those who had learning goals processed the course material more deeply and were more likely to integrate the course material across units. These students also earned higher grades than their peers who did not endorse learning goals, even after Grant and Dweck controlled for SAT scores. Whether these effects are mediated by students' confidence in their ability to master the material needs to be assessed.

Educational interventions designed to increase the prevalence of learning/mastery goals do lead to increases in engagement with, and mastery of, STEM material. For example, Farrell and Dweck (1985) found that eighth-grade children instructed to have learning goals in a week-long unit in their science class attained higher scores on a transfer-of-skills test, worked harder on the test, and were more likely to try to apply what they learned to solve novel problems compared with children instructed to have performance goals. Similarly, interventions designed to change children's theories from entity to incremental produced performance and motivational gains (Blackwell, Trzesniewski, & Dweck, 2007). Finally, the National Research Council and Institute of Medicine (2004) report on engaging schools stressed the importance of teachers and school personnel having high expectations for all students' ability to master the material being taught precisely be-

cause teachers' confidence in their students' ability to master the material is essential for supporting the students' confidence in their own ability. Unfortunately, negative racial, ethnic, gender, and social class stereotypes can lead teachers and school districts to communicate low expectations for the academic achievements of some groups of students. Such processes are quite prevalent in the STEM fields.

Full engagement in learning STEM also requires a desire or willingness to do the task (Wigfield et al. 2006). Research has helped us understand the psychological and social factors influencing the answer to the question "Do I want to do this task?" as well as provided methods to increase the odds that the answer will be yes. Two of the most widely researched psychological influences relate to intrinsic motivation and both personal and social identities.

On intrinsic motivation and interest, beginning with the early work of Lepper and his colleagues and continuing with the work of Deci and Ryan and their colleagues, psychologists have shown the potential benefits of intrinsic motivation (i.e., doing something purely for the sake of personal enjoyment; Deci & Ryan, 2002) and the potential pitfalls of extrinsic motivation (i.e., doing something for an external reward; Deci, Koestner, & Ryan, 1999; Lepper & Greene, 1978). Similarly, interest theorists have shown that students process interesting STEM materials much more deeply and fully than noninteresting STEM materials (Hidi, 1990). Intrinsic motivation and interest can be cultivated by using different teaching strategies. Cordova and Lepper (1996) suggested two ways in which this might occur: through the use of contextualization and of personalization and choice. Teachers often seek to present information in an abstract form, deliberately decontextualizing it from the students' everyday experience. This is thought to give the student the ability to generalize the abstract knowledge in different domains. This manner of presentation, however, often has the unfortunate consequence of undermining children's interest in the subject matter because they do not see any practical utility in it or how it could be applied to their everyday curiosities and interests. By harnessing children's intrinsic curiosities about their world and applying abstract concepts, such as math, to experiences they come across every day (e.g., at home), teachers can likely increase children's intrinsic motivation (Bruner, 1966). Second, by using characters, themes, objects, and so forth that are already of high interest to children, educators can personalize difficult and abstract concepts (e.g., teaching fractions by dividing portions of a pizza), which makes them more accessible and ultimately more memorable (Hidi, 1990; Linn, Bell, & Davis, 2004; Linn & Hsi, 2000).

Other groups of developmental and social psychologists have stressed the role of personal and social identities for students' involvement in STEM. Eccles and her colleagues focused on what they call attainment value, which they define in terms of the fit between activities such as STEM courses and STEM professions and the individual's own needs, personal interests, and personal values. Longitudinal studies have shown that gender differences in students' decisions to enroll in advanced mathematics are

mediated primarily by gender differences in the value that the students attached to mathematics. Furthermore, and more important, young women think that advanced math and physics are less important and enjoyable than the many other advanced high school courses they could be taking instead, particularly courses linked to the biological and social sciences. Not surprisingly, females are now as likely, if not more likely, than their male counterparts to major in the biological and social sciences and to go into advanced training and careers in the medical, biological, and social sciences. In their longitudinal follow-ups of adolescents as they make the transition to adulthood, Eccles and her colleagues have found that females' STEM career decisions were closely linked to their desire to have a career that allowed them to directly help other people: Women with STEM interests and a desire to help other people avoided engineering in favor of the biological and medical sciences (Eccles et al., 1999). Interestingly, interventions based on making physics more interesting to females by using more human biological examples of physical principles have been quite successful at increasing females' engagement in physics classes.

Recently, social psychologists have also examined the role of social identities and social stereotypes as important sociocultural factors influencing the underrepresentation of women and minorities in STEM-related areas. For instance, Steele and Aronson's (1995) work on "stereotype threat" has shown that when put in an academic performance situation that is believed to be diagnostic of their intellectual ability, and when their race is made salient, African American students feel an extra burden to perform well—so as to not confirm, to themselves or others, the negative stereotype. This extra burden of anxiety interferes with their performance and paradoxically impairs it. Much of this work has focused specifically on mathematics.

Gender stereotypes about math and science also run deep, and stereotype-threat effects have been found for women in domains associated with negative gender stereotypes, such as mathematics, when their gender identity is made salient. For example, in one study some women were led to believe that their performance on a particular math task was gender relevant, and others were led to believe that the same math task was not gender relevant. Those participants who believed their performance was relevant to gender performed worse in comparison to men; and the participants who believed their performance was not related to gender performed as well as men (Spencer, Steele, & Quinn, 1999).

It is interesting that positive stereotypes also affect performance in mathematics. Shih, Pittinsky, and Ambady (1999) subtly activated different aspects of the identity of Asian American women and examined their mathematics performance. In the domain of mathematics in this culture, Asians are positively stereotyped, whereas women are negatively stereotyped. In accordance with prevailing sociocultural stereotypes, participants whose gender identity was activated performed worse than control participants, but those whose Asian identity was activated performed significantly better. Thus social identities and their associated

sociocultural stereotypes can have significant effects on academic performance. These effects are found in children as young as 5 to 7 years of age (Ambady, Bernieri, & Richeson, 2000).

Fortunately, there are ways to protect against the negative effects of stereotypes. For example, Ambady, Paik, Steele, Owen-Smith, and Mitchell (2004) have found that stereotype threat can be attenuated through individuation. Women in a gender-primed condition who focused on other aspects of their individual identity performed significantly better than women who were in a gender-primed but nonindividuated condition and as well as women in a non-gender-primed condition. Thus, individuation might be one potential mechanism that negatively stereotyped groups can use to buffer stereotype threat. Since stereotype threat may provide clues as to why fewer minorities and women excel at STEM disciplines and careers, additional research should focus on other fruitful means to assuage its negative consequences.

In summary, psychological evidence supports the conclusion that motivational beliefs and the social processes linked to the development of these beliefs explain a substantial amount of individual and group differences in both learning and engagement in STEM. Furthermore, we know that student confidence and interest in STEM subject areas decline on average across the K–12 school years. Finally, we know that interventions based on the motivational principles outlined in this section can be effective in both decreasing group differences in, and increasing average levels of, students' engagement and performance in STEM subject areas. However, many specifics remain to be worked out, and it is telling that a recent Institute of Education Sciences Practice Guide on encouraging female participation in the STEM disciplines could endorse many suggested practices only at low or moderate levels of confidence in the evidence (Halpern et al., 2007). More collaborative research is needed between psychologists and educational researchers to design programs that can be implemented in large-scale reform initiatives and to identify which programs work best for which subpopulations.

Assessment

We focus on assessment in the context of the No Child Left Behind Act of 2001—a policy initiative that has mandated annual assessment of mathematics and, more recently, increased testing in science with the goal of improving learning. Research in the learning sciences draws attention to the potential consequences of this policy (National Research Council, 1999). However, assessments by themselves do not improve performance. To make increased assessment meaningful and effective, the assessments should mandate the sorts of activities that characterize a science-literate individual. When they are effective, tests aligned with an effective curriculum can increase the impact of the curriculum. Ideally, tests themselves will serve as learning events, contributing to the curriculum and at the same time measuring student progress and informing teachers of instructional needs. In the worst scenario, tests have the unintended consequence of motivating unproductive cur-

ricular changes such as increased test practice or elimination of curricular activities that are not directly measured by the test.

Analysis of state mathematics and science tests, for example, shows that they rarely measure important abilities such as using evidence to form arguments, interpreting contemporary dilemmas, or comprehending the nature of science. As a result, tests deter teachers from teaching the skills that are valuable for science-literate individuals. Some teachers infer that practice on test items would be the best way to improve performance, and textbooks regularly include standardized items as part of class tests. When they are evaluated on standardized test performance, many math and science teachers abandon inquiry goals and teaching for understanding and substitute memorization and drill on multiple-choice questions requiring the recall of facts (Au, 2007). Although research shows that improving performance on multiple-choice, fact-oriented tests results from instruction that stresses coherent understanding (Cobb, Wood, Yackel, & Perwitz, 1992), schools and teachers are often afraid to depart from practices that align with the perceived demands of the assessment.

To ensure that increased assessment impacts learning, we need to understand what should be measured and how the results can lead to improved teaching and learning. As articulated in the National Academy of Sciences publication titled *Knowing What Students Know* (National Research Council, 2001c), we need improved design, use, and interpretation of assessments to ensure that they contribute to learning. The report underscores the value of collaborative research, calling for “increased and sustained multidisciplinary collaboration around theoretical and practical matters of assessment” (p. 11). *Knowing What Students Know* specifically articulates what the authors of the report call “the assessment triangle” (p. 296). The triangle links a model of student cognition and learning in the domain, beliefs about the kinds of observations that will provide evidence of students’ competencies, and an interpretation process for making sense of the evidence. The authors of the report call for using the assessment triangle to iteratively refine these three elements of the assessment in order to align the goals of instruction with the outcome measures. The report is replete with examples of inappropriate test use resulting from limitations in implementation of the assessment triangle. Lack of alignment can lead to serious errors in both designing curriculum materials (when the goals of the curriculum materials do not reflect the goals of the assessment) and in assessing students (when students do not have the opportunity to learn the material tested).

In addition, to implement effective solutions, decision makers need more informative models of student cognition and learning, curriculum designers need to design materials based on research findings and to conduct research on how instruction contributes to long-term understanding, and schools need to identify combinations of instruction and assessment that jointly lead to improved science understanding. Ideally, individuals making decisions about instruction will have evidence about how specific materials provide opportunities for students to learn. In addition,

decision makers need confidence that the assessments offer items that have characteristics aligned with our best understanding of student cognition and learning in mathematics and science.

Although the various stakeholders in the field of assessment do not agree about the construct that underlies science and mathematics learning, investigators have increased our understanding about how students learn and how assessments tap the learning that has occurred (National Research Council, 1999, 2000, 2006a). Measuring literacy has been an important focus of research in science and mathematics education. There is evidence that valid and reliable measures of the kinds of complex reasoning that students need in order to operate in today’s world can be used in research and in large-scale assessments. Research on assessment offers promising ways to measure argumentation (Osborne, Erduran, & Simon, 2004), integrated understanding (Clark & Linn, 2003; Linn & Hsi, 2000), coherent understanding (DeBoer, 2005), and understanding of the nature of scientific advance (diSessa, 2000).

We strongly encourage research programs to develop and validate these kinds of tests in current educational settings. To illustrate, the Technology Enhanced Learning and Science (TELS) center has conducted a large-scale cohort comparison study to assess the impact of inquiry modules delivered using a technology-enhanced learning environment and powerful visualizations of scientific phenomena on student learning (Linn, Lee, Tinker, Husic, & Chiu, 2006). In this study, the TELS center participants contrasted current high-stakes items typically administered in a multiple-choice format with explanation items from some high-stakes tests, as well as from research. The investigators found that the items that required students to develop an argument and explain their reasoning were far more sensitive to inquiry instruction than were the items that asked students to select an answer in a multiple-choice format.

For the explanation items, the TELS research group found that it is important not only to have items that require reasoning but also to have scoring rubrics that capture the accomplishments. By scoring high-stakes test items using a rubric that rewarded making connections and building arguments, TELS increased the sensitivity of these items. With the rescoring, these items were effective at distinguishing between inquiry instruction and typical instruction. Aligning the goals of instruction with the assessment and the scoring rubric is crucial to gaining the benefit promised by the No Child Left Behind Act of 2001.

Technology-enhanced instruction can provide a far more detailed set of information for teachers and students than is possible with typical curriculum materials. Using materials developed and delivered with a learning environment allows gathering of information about student performance in the moment. Computer-delivered instruction can include embedded assessments that ask students to reflect on their understanding or to judge their own learning, and the computer can construct quite sophisticated models not only of students’ subject matter knowledge but also of their strategies for using, and sometimes “gaming,” such sys-

tems (Alevin, Stahl, Schworm, Fischer, & Wallace, 2003; Koedinger & Alevin, 2007). They can also log the kinds of investigations that learners conduct. This information can guide learners, inform the design of instructional materials, and help teachers use their time effectively. The information that these environments can gather is relatively easily communicated to teachers. Teachers can use this information to modify their instruction and to improve the activities that their students encounter.

In summary, assessment is currently at a rather primitive level. We have the opportunity, using technology-enhanced materials and current research in cognition, to gain a far more precise and detailed understanding of the trajectories that students follow, the kinds of difficulties that they face, and the sorts of learning experiences that advance their understanding. Similarly, we have an opportunity to gather very powerful and useful information from a broad range of indicators about teacher learning, teacher performance, and teacher response to evidence of student progress. Furthermore, teachers can use this broad array of information to determine what works for the students they teach.

We offer a number of recommendations. First, as each of the issues discussed in this report suggests, interdisciplinary research has the potential to improve STEM learning. As a starting point, we encourage the convening of summits of all stakeholders to discuss contemporary topics and come up with a roadmap for research efforts in this field. Multidisciplinary collaborations need to involve psychometricians, learning scientists, STEM educators, discipline specialists, technologists, and classroom teachers. Partners will need to jointly negotiate understanding of the cognition of student learning, the design of observations that will provide evidence of student competencies, and the interpretation of the results for classroom use, student use, policymaking, and long-range planning. To build consensus and support an emergent research program, these summits should include the following possible foci:

- How can we enable teachers to take advantage of the diagnostic information available in classrooms and to identify additional sources of information?
- How can we create assessments that measure the goals of science articulated in recent reports such as *Taking Science to School* (National Research Council, 2007) and *Knowing What Students Know* (National Research Council, 2001c)?
- How can we align assessment with instruction, consistent with the recommendations of *Knowing What Students Know* (National Research Council, 2001c)?

Second, we recommend that funds be allocated to support important and promising questions that clearly need to be researched. These include the following:

- research to understand how the current high-stakes tests are influencing motivation, as well as understanding
- research to understand how technology can improve

the assessments used in mathematics and science and provide more immediate feedback to teachers

- research to investigate the relationship between knowledge gained in classrooms, in laboratory experiences, and in field settings, in order to better understand the relationships between what has been called formal and informal learning, as well as to assess factors such as anxiety and stereotype threat.

Conclusion

Psychology is a broad discipline that encompasses many areas of research important to successful education in mathematics and science. In addition, it is a key discipline along with cognitive science, neuroscience, computer science, and other fields in the establishment of a new science of learning that has exciting potential to provide deep insights into the nature of human learning and how best to enhance it at all ages and in a variety of disciplines. In order to make these goals realizable, however, psychology will need to learn to do research in multidisciplinary contexts, in specific public policy environments, and with an eye to useful application as well as pure knowledge. Such alliances are in fact emerging, and can be facilitated by professional organizations including the American Psychological Association and the Society for Research in Child Development.

REFERENCES

- Alevin, V., Stahl, E., Schworm, S., Fischer, F., & Wallace, R. M. (2003). Help seeking and help design in interactive learning environments. *Review of Educational Research, 73*, 277–320.
- Ambady, N., Bernieri, F. J., & Richeson, J. A. (2000). Toward a histology of social behavior: Judgmental accuracy from thin slices of the behavioral stream. In M. P. Zanna (Ed.), *Advances in experimental social psychology* (Vol. 32, pp. 201–271). San Diego, CA: Academic Press.
- Ambady, N., Paik, S., Steele, J., Owen-Smith, A., & Mitchell, J. (2004). Deflecting negative self-relevant stereotype activation: The effects of individuation. *Journal of Experimental Social Psychology, 40*, 401–408.
- Amsel, E., & Brock, S. (1996). The development of evidence evaluation skills. *Cognitive Development, 11*, 523–550.
- Anderman, E. M., Maehr, M. L., & Midgley, C. (1999). Declining motivation after the transition to middle school: Schools can make a difference. *Journal of Research and Development in Education, 32*, 131–147.
- Au, W. (2007). High-stakes testing and curricular control: A qualitative metasynthesis. *Educational Researcher, 36*, 258–267.
- Bandura, A. (1997). *Self-efficacy: The exercise of control*. New York: W. H. Freeman.
- Beck, S. R., & Robinson, E. J. (2001). Children's ability to make tentative interpretations of ambiguous messages. *Journal of Experimental Child Psychology, 79*, 95–114.
- Behr, M. J., Lesh, R., Post, T. R., & Silver, E. A. (1983). Rational number concepts. In R. Lesh & M. Landau (Eds.), *Acquisition of mathematics concepts and processes* (pp. 91–126). New York: Academic Press.
- Blackwell, L., Trzesniewski, K., & Dweck, C. S. (2007). Implicit theories of intelligence predict achievement across an adolescent transition: A longitudinal study and an intervention. *Child Development, 78*, 246–263.
- Bruner, J. S. (1966). *Toward a theory of instruction*. Cambridge, MA: Harvard University Press.
- Bruner, J. S., Goodnow, J. J., & Austin, G. A. (1956). *A study of thinking*. New York: Wiley.

- Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.
- Carey, S. (1988). Conceptual differences between children and adults. *Mind and Language*, 3, 167–181.
- Carey, S. (1991). Knowledge acquisition: Enrichment or conceptual change? In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (pp. 257–291). Hillsdale, NJ: Erlbaum.
- Chen, Z., & Klahr, D. (1999). All other things being equal: Acquisition and transfer of the control of variables strategy. *Child Development*, 70, 1098–1120.
- Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Glaser (Ed.), *Cognitive models of science: Minnesota Studies in the Philosophy of Science* (pp. 129–186). Minneapolis: University of Minnesota Press.
- Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences*, 14(2), 161–199.
- Clark, D., & Linn, M. C. (2003). Designing for knowledge integration: The impact of instructional time. *Journal of the Learning Sciences*, 12, 451–494.
- Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions. *Journal of Research in Science Teaching*, 30, 1241–1257.
- Cobb, P., Wood, T., Yackel, E., & Perlwitz, M. (1992). A longitudinal, follow-up assessment of a second-grade problem-centered mathematics project. *Educational Studies in Mathematics*, 23, 483–504.
- Cordova, D. I., & Lepper, M. R. (1996). Intrinsic motivation and the process of learning: Beneficial effects of contextualization, personalization, and choice. *Journal of Educational Psychology*, 88, 715–730.
- Correa, J., Nunes, T., & Bryant, P. (1998). Young children's understanding of division terms in a noncomputational task. *Journal of Educational Psychology*, 90, 321–329.
- DeBoer, G. E. (2005, January). Standardizing test items. *Science Scope*, 28(4), 10–11.
- Deci, E. L., Koestner, R., & Ryan, R. M. (1999). A meta-analytic review of experiments examining the effects of extrinsic rewards on intrinsic motivation. *Psychological Bulletin*, 125, 627–668.
- Deci, E. L., & Ryan, R. M. (2002). The paradox of achievement: The harder you push, the worse it gets. In J. Aronson (Ed.), *Improving academic achievement: Impact of psychological factors on education* (pp. 61–87). San Diego, CA: Academic Press.
- diSessa, A. A. (2000). *Changing minds: Computers, learning and literacy*. Cambridge, MA: MIT Press.
- Duncan, G. J., Claessens, A., Huston, A. C., Pagani, L. S., Engel, M., Sexton, H., et al. (2007). School readiness and later achievement. *Developmental Psychology*, 43, 1428–1446.
- Dweck, C. S. (1986). Motivational processes affecting learning. *American Psychologist*, 41, 1040–1048.
- Dweck, C. S. (2002). The development of ability conceptions. In A. Wigfield & J. S. Eccles (Eds.), *Development of achievement motivation* (pp. 57–88). San Diego, CA: Academic Press.
- Eccles, J. S., Barber, B., & Josefovich, D. (1999). Linking gender to educational, occupational, and recreational choices: Applying the Eccles et al. model of achievement-related choices. In W. B. Swann, J. H. Langlois, & L. A. Gilbert (Eds.), *Sexism and stereotypes in modern society: The gender science of Janet Spence* (pp. 153–192). Washington, DC: American Psychological Association.
- Eccles, J. S., Wigfield, A., & Schiefele, U. (1998). Motivation to succeed. In W. Damon (Series Ed.) & N. Eisenberg (Vol. Ed.), *Handbook of child psychology* (5th ed., Vol. 3, pp. 1017–1095). New York: Wiley.
- Farrell, E., & Dweck, C. S. (1985). *The role of motivational processes in transfer of learning*. Unpublished manuscript, Harvard University.
- Fay, A., & Klahr, D. (1996). Knowing about guessing and guessing about knowing: Preschoolers' understanding of indeterminacy. *Child Development*, 67, 689–716.
- Feigenson, L., & Carey, S. (2003). Tracking individuals via object-files: Evidence from infants' manual search. *Developmental Science*, 6, 568–584.
- Frydman, O., & Bryant, P. (1988). Sharing and the understanding of number equivalence by young children. *Cognitive Development*, 3, 323–339.
- Gentner, D., & Toupin, C. (1986). Systematicity and surface similarity in the development of analogy. *Cognitive Science: A Multidisciplinary Journal*, 10, 277–300.
- Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, 15, 1–38.
- Gopnik, A., & Schulz, L. (Eds.). (2007). *Causal learning: Psychology, philosophy, and computation*. New York: Oxford University Press.
- Goswami, U. (1989). Relational complexity and the development of analogical reasoning. *Cognitive Development*, 4, 251–268.
- Grant, H., & Dweck, C. S. (2003). Clarifying achievement goals and their impact. *Journal of Personality and Social Psychology*, 85, 541–553.
- Gross, P., Goodenough, U., Lerner, L. S., Haack, S., Schwartz, M., Schwartz, R., & Finn, C. E., Jr. (2005). *The state of state science standards 2005*. Retrieved March 16, 2009, from Thomas B. Fordham Institute website: http://www.edexcellence.net/detail/news.cfm?news_id=352.
- Halpern, D., Aronson, J., Reimer, N., Simpkins, S., Star, J., & Wentzel, K. (2007). *Encouraging girls in math and science* (NCER 2007–2003). Washington, DC: National Center for Education Research, Institute of Education Sciences, U.S. Department of Education. Retrieved March 16, 2009, from <http://ies.ed.gov/ncer/pubs/practiceguides/20072003.asp>.
- Hidi, S. (1990). Interest and its contribution as a mental resource for learning. *Review of Educational Research*, 60, 549–571.
- Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, 42, 99–107.
- Huttenlocher, J., Jordan, N. C., & Levine, S. C. (1994). A mental model for early arithmetic. *Journal of Experimental Psychology: General*, 123, 284–296.
- Hyde, J. S., & Linn, M. C. (2006). Gender similarities in mathematics and science. *Science*, 27, 599–600.
- Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence*. London: Routledge & Kegan Paul.
- Kirschner, P. A., Sweller, J., & Clark, R. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential and inquiry-based teaching. *Educational Psychologist*, 41, 75–86.
- Klahr, D. (2000). *Exploring science: The cognition and development of discovery processes*. Cambridge, MA: MIT Press.
- Klibanoff, R., Levine, S. C., Huttenlocher, J., Vasilyeva, M., & Hedges, L. (2006). Preschool children's mathematical knowledge: The effect of teacher "math talk." *Developmental Psychology*, 42, 59–69.
- Koedinger, K., & Alevan, V. (2007). Exploring the assistance dilemma in experiments with Cognitive Tutors. *Educational Psychology Review*, 19, 239–264.
- Koslowski, B. (1996). *Theory and evidence: The development of scientific reasoning*. Cambridge, MA: MIT Press.
- Kuhn, D. (2007). Is direct instruction the answer to the right question? *Educational Psychologist*, 42, 109–113.
- Kuhn, D., Garcia-Mila, M., Zohar, A., & Andersen, C. (1995). Strategies of knowledge acquisition. *Monographs of the Society for Research in Child Development*, 60(4, Serial No. 245).
- Kuhn, D., & Park, S. (2005). Epistemological understanding and intellectual values. *International Journal of Educational Research*, 43, 111–124.
- Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.
- Lakoff, G., & Nunez, R. E. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being*. New York: Basic Books.
- Latour, B. (1999). *Pandora's hope: Essays on the reality of science studies*. London: Cambridge University Press.
- Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy. In W. Damon, R. Lerner, K. A. Renninger, & I. E. Sigel (Eds.), *Handbook of child psychology: Vol. 4. Child psychology in practice* (6th ed., pp. 153–196). Hoboken, NJ: Wiley.
- Lepper, M. R., & Greene, D. (1978). *The hidden costs of reward*. Hillsdale, NJ: Erlbaum.
- Leslie, A. M. (1987). Pretense and representation: The origins of "theory of mind." *Psychological Review*, 94, 412–426.
- Li, J., & Klahr, D. (2006). The psychology of scientific thinking: Impli-

- cations for science teaching and learning. In J. Rhoton & P. Shane (Eds.), *Teaching science in the 21st century* (National Science Teachers Association and National Science Education Leadership Association). Arlington, VA: NSTA Press.
- Linn, M. C., Bell, P., & Davis, E. A. (2004). Specific design principles: Elaborating the scaffolded knowledge integration framework. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 315–340). Mahwah, NJ: Erlbaum.
- Linn, M. C., & Hsi, S. (2000). *Computers, teachers, and peers: Science learning partners*. Mahwah, NJ: Erlbaum.
- Linn, M. C., Lee, H.-S., Tinker, R., Husic, F., & Chiu, J. L. (2006, August 25). Teaching and assessing knowledge integration in science. *Science*, *313*, 1049–1050.
- Longino, H. (2002). *The fate of knowledge*. Princeton, NJ: Princeton University Press.
- Mack, N. K. (1993). Learning rational numbers with understanding: The case of informal knowledge. In T. P. Carpenter, E. Fennema, & T. A. Romberg (Eds.), *Rational numbers: An integration of research. Studies in mathematical thinking and learning* (pp. 85–105). Hillsdale, NJ: Erlbaum.
- Mack, N. K. (2000). Long-term effects of building on informal knowledge in a complex content domain: The case of multiplication of fractions. *Journal of Mathematical Behavior*, *19*, 307–332.
- Mack, N. K. (2001). Building on informal knowledge through instruction in a complex content domain: Partitioning, units, and understanding multiplication of fractions. *Journal for Research in Mathematics Education*, *32*, 267–295.
- Michaels, S., Shouse, A. W., & Schweingruber, H. A. (2007). *Ready, set, science! Putting research to work in K-8 science classrooms*. Washington, DC: National Academies Press.
- Midgley, C. (2002). *Goals, goal structures, and adaptive learning*. Mahwah, NJ: Erlbaum.
- Miller, K. F. (1984). Child as the measurer of all things: Measurement procedures and the development of quantitative concepts. In C. Sophian (Ed.), *Origins of cognitive skills: The Eighteenth Annual Carnegie Symposium on Cognition* (pp. 193–228). Hillsdale, NJ: Erlbaum.
- National Academy of Sciences, National Academy of Engineering, & Institute of Medicine. (2005). *Rising above the gathering storm: Energizing and employing America for a brighter future*. Washington, DC: National Academies Press.
- National Mathematics Advisory Panel. (2008). *Foundations for success: The final report of the National Mathematics Advisory Panel*. Washington, DC: U.S. Department of Education.
- National Research Council. (1999). *High stakes: Testing for tracking, promotion, and graduation* (J. P. Heubert & R. M. Hauser, Eds.). Washington, DC: National Academy Press.
- National Research Council. (2000). *How people learn: Brain, mind, experience, and school* (J. D. Bransford, A. L. Brown, & R. R. Cocking, Eds.). Washington, DC: National Academies Press.
- National Research Council. (2001a). *Adding it up: Helping children learn mathematics* (J. Kilpatrick, J. Swafford, & B. Findell, Eds.). Washington, DC: National Academy Press.
- National Research Council. (2001b). *Eager to learn: Educating our preschoolers* (B. T. Bowman, M. S. Donovan, & M. S. Burns, Eds.). Washington, DC: National Academy Press.
- National Research Council. (2001c). *Knowing what students know: The science and design of educational assessment* (J. W. Pellegrino, N. Chudowsky, & R. Glaser, Eds.). Washington, DC: National Academy Press.
- National Research Council. (2006a). *America's lab report: Investigations in high school science* (S. R. Singer, M. I. Hilton, & H. A. Schweingruber, Eds.). Washington, DC: National Academies Press.
- National Research Council. (2006b). *Learning to think spatially: GIS as a support system in the K-12 curriculum*. Washington, DC: National Academies Press.
- National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8* (R. A. Duschl, H. A. Schweingruber, & A. W. Shouse, Eds.). Washington, DC: National Academies Press.
- National Research Council & Institute of Medicine. (2000). *From neurons to neighborhoods: The science of early childhood development* (J. P. Shonkoff & D. A. Phillips, Eds.). Washington, DC: National Academy Press.
- National Research Council & Institute of Medicine. (2004). *Engaging schools: Fostering high school students' motivation to learn*. Washington, DC: National Academies Press.
- National Science and Technology Council. (2006, October 6). *Review and appraisal of the federal investment in STEM education research*. Retrieved March 16, 2009, from <http://www.ostp.gov/galleries/NSTC%20Reports/STEMEducationResearchOctober06.pdf>
- National Science Foundation. (2008). *Women, minorities, and persons of disability in science and engineering* (NSF 07–315). Arlington, VA: Author. (Available at <http://www.nsf.gov/statistics/wmpd/employ.htm>)
- No Child Left Behind Act of 2001, Pub. L. No. 107–110, 115 Stat. 1425 (2002).
- Osborne, J., Erduran, S., & Simon, S. (2004). Enhancing the quality of argumentation in school science. *Journal of Research in Science Teaching*, *41*, 994–1020.
- Paik, J. H., & Mix, K. S. (2008). Do Korean fraction names promote part-whole reasoning? *Journal of Cognition and Development*, *9*, 145–170.
- Pajares, F. (1996). Self-efficacy beliefs in academic settings. *Review of Educational Research*, *66*, 543–578.
- Pashler, H., Bain, P., Bottge, B., Graesser, A., Koedinger, K., McDaniel, M., & Metcalfe, J. (2007). *Organizing instruction and study to improve student learning: A practice guide* (NCER 2007–2004). Washington, DC: National Center for Education Research, Institute of Education Sciences, U.S. Department of Education.
- Ramani, G. B., & Siegler, R. S. (2008). Promoting broad and stable improvements in low-income children's numerical knowledge through playing number board games. *Child Development*, *79*, 375–394.
- Ruffman, T., Perner, J., Olson, D. R., & Doherty, M. (1993). Reflecting on scientific thinking: Children's understanding of the hypothesis–evidence relation. *Child Development*, *64*, 1617–1636.
- Schmidt, H. G., Loyens, S. M. M., van Gog, T., & Paas, F. (2007). Problem-based learning is compatible with human cognitive architecture: Commentary on Kirschner, Sweller, and Clark (2006). *Educational Psychologist*, *42*, 91–97.
- Shih, M., Pittinsky, T. L., & Ambady, N. (1999). Stereotype susceptibility: Identity salience and shifts in quantitative performance. *Psychological Science*, *10*, 81–84.
- Sophian, C., Garyantes, D., & Chang, C. (1997). When three is less than two: Early developments in children's understanding of fractional quantities. *Developmental Psychology*, *33*, 731–744.
- Spencer, S., Steele, C. M., & Quinn, D. (1999). Stereotype threat and women's math performance. *Journal of Experimental Social Psychology*, *35*, 4–28.
- Steele, C. M., & Aronson, J. (1995). Stereotype threat and the intellectual test performance of African Americans. *Journal of Personality and Social Psychology*, *69*, 797–811.
- Stokes, D. E. (1997). *Pasteur's quadrant: Basic science and technological innovation*. Washington, DC: Brookings Institution Press.
- Sweller, J., Kirschner, P. A., & Clark, R. (2007). Why minimally guided teaching techniques do not work: A reply to commentaries. *Educational Psychologist*, *42*, 115–121.
- Tschirgi, J. E. (1980). Sensible reasoning: A hypothesis about hypotheses. *Child Development*, *51*, 1–10.
- Van de Walle, G. A., Carey, S., & Prevor, M. (2000). Bases for object individuation in infancy: Evidence from manual search. *Journal of Cognition and Development*, *1*, 249–280.
- Vellom, R. P., & Anderson, C. W. (1999). Reasoning about data in middle school science. *Journal of Research in Science Teaching*, *36*, 179–199.
- Vosniadou, S., & Brewer, W. F. (1994). Mental models of the day/night cycle. *Cognitive Science*, *18*, 123–183.
- Wason, P. C. (1960). On the failure to eliminate hypotheses in a conceptual task. *Quarterly Journal of Experimental Psychology*, *12*, 129–140.
- Wason, P. C. (1968). Reasoning about a rule. *Quarterly Journal of Experimental Psychology*, *20*, 273–281.
- White, G., Frishkoff, G., & Bullock, M. (2008). Bridging the gap between psychological science and educational policy and practice. In S. K. Thurman & C. A. Fiorello (Eds.), *Applied cognitive research in K–3 classrooms* (pp. 227–264). New York: Routledge.
- Wigfield, A., Eccles, J. S., Schiefele, U., Roeser, R. W., & Davis-Kean, P. (2006). Development of achievement motivation. In W. Damon (Series Ed.) & N. Eisenberg (Vol. Ed.), *Handbook of child psychology* (6th ed., Vol. 3, pp. 933–1002). New York: Wiley.