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Development of Executive Functions: Implications for Educational Policy and Practice

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Abstract

Executive functions refer to top–down processes utilized in goal-directed behavior. Executive functions and academic achievement relate robustly, from early childhood through adolescence. Executive functions and their neural networks appear to be malleable, and environments can support their development. Varied approaches, including educational curricula, structured physical exercise, and computer-based training, can improve executive functions. The intervention work suggests that children who are most "at-risk" demonstrate the largest gains, but evidence of far transfer to academic achievement or other behavioral outcomes that are important to schools is at this point only promising. The review highlights developmental considerations for measurement and intervention, and discusses implications for schools in supporting children's development of executive functions. Policy implications of the scientific findings suggest strategies for providing environments that foster the development of executive functions.

Keywords

executive functions, development, interventions, assessment, education, cognitive training

Tweet

Schools can structure learning environments to foster children's development of executive functions that aid goal-directed behavior.

Key Points

- Executive functions are associated with academic success.
- Executive functions are malleable throughout childhood and adolescence.
- Few educational approaches so far capitalize on the malleability of neural networks and target executive functions for intervention.
- Training and interventions demonstrate some success, but there is limited evidence that gains transfer to academic outcomes.
- Schools can structure learning environments to support the development of executive functions.

Introduction

Executive functions (EFs) refer to top–down processes (inhibition, working memory, and cognitive flexibility) activated in the context of goal-directed behavior. EFs help us maintain problem-specific information active in our working memory, ignore distracting information, and inhibit responses that impede task-relevant goals. EFs are not only an essential component of self-regulation (Moffitt et al., 2011) but also broadly applied across a wide range of daily-life activities (Diamond, 2013). Longitudinal studies demonstrate that EFs in childhood are strongly associated with academic achievement (Best, Miller, & Naglieri, 2011; Diamond, 2013; St. Clair-Thompson & Gathercole, 2006), social adjustment, and myriad adult outcomes, such as mental and physical health and economic success (Moffitt et al., 2011).

Twenty years ago, the term *executive functions* was obscure, and few educators would have been familiar with it. The term now enjoys widespread use in the developmental literature, and an extraordinary number of research articles in education journals now reference it. There is also a growing interest in targeting EFs for intervention. Interventions in educational research arise from different perspectives and include testing the efficacy of specific curricula, physical activity, and computer-based cognitive training (Diamond & Ling, 2015). The interest in intervention is linked to discoveries in neuroscience, suggesting that EFs are malleable throughout childhood and adolescence (Casey, Tottenham, Liston, & Durston, 2005).

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This malleable quality of EFs has spurred a notable growth in cognitive training programs, with bold enticements from commercially available computer-based programs to "train your child's brain" and promises to "boost working memory" and "solve attention problems." The massive proliferation of brain training programs represents a broader problem with how scientific evidence makes its way into the public discourse and taken up by industry. These dangers also concern learning styles (Pashler, McDaniel, Rohrer, & Bjork, 2008), educational apps for language acquisition (Hirsh-Pasek et al., 2015), and applications in schools for grit (Duckworth, 2016). As such, we proceed cautiously on the recommendations front, highlighting the benefits of applying principles derived from developmental science, rather than promoting specific approaches.

A developmental approach guides this broad overview of the scientific research on EFs as related to education and its outcomes. Specifically, the article discusses definitional ambiguities, development and measurement of EFs, as well as promises and pitfalls of existing EF interventions. Considering what we know about EFs, we extrapolate from the science with an eye toward the positive—outlining ways to think more broadly about the evidence, with implications for educational practice and policy.

Defining Terms

EFs, as top–down monitoring and control processes, activate in the context of goal-directed behavior (Diamond, 2013). Core EFs include inhibition (controlling one's behavior, attention, thoughts, emotions), working memory (temporarily holding and using information), and cognitive flexibility (effectively switching between tasks; Diamond, 2013; Miyake et al., 2000; Zelazo et al., 2013).

Inhibitory control is a foundational EF—it allows students to control dominant responses in their attention, thoughts, emotions, and behaviors, and do what is right to meet the task and context demands. An example in a classroom context is overcoming the desire to blurt out an answer without raising one's hand. Older children utilize inhibition to rally their attention to the task at hand, even when the task is not intrinsically interesting. For example, they curb the desire to pursue competing interests, such as getting on *Facebook*, rather than completing an online study quiz. Working memory entails simultaneously storing and processing information. In mental math, for example, students have to keep two numbers in mind, bring to the forefront of their memories the rules for multiplication, use all this information to make the calculation, and generate a solution. As such, working memory underlies reasoning and problem solving. Cognitive flexibility, or the ability to shift mental sets, allows students to manage changing demands in classrooms. At the simplest level, cognitive flexibility enables students to seamlessly switch between classroom activities—from individual note taking to collaborative problem solving. Cognitive flexibility also enables applying novel strategies to an old task.

These core EFs underlie higher-order EF skills—planning, reasoning, and problem solving (Diamond, 2013). The higher-order skills harness the core EFs as top–down iterative processes that include adjusting to meet task demands. To illustrate, team-based projects in middle school science classrooms assign student pairs to, for example, identify factors that influence the boiling point of water. Successfully generating solutions requires not only preparatory planning and organization but also multistep experimentation, adjusting based on prior knowledge and extending from insights gained during the task.

Definitional ambiguities complicate EFs. For example, EFs differ from effortful control. Effortful control, unlike EFs, is emotion based and develops earlier than EF (Diamond, 2013). Furthermore, effortful control and EFs make independent contributions to early math and literacy skills (Blair & Razza, 2007). Also, some debate whether EFs are a unit or a set of dissociable components (Espy, Sheffield, Wiebe, Clark, & Moehr, 2011; Huizinga, Dolan, & van der Molen, 2006; Miyake et al., 2000). The growing consensus is that EFs are related but dissociable components (Miyake et al., 2000) that have different developmental growth trajectories (Best & Miller, 2010).

Neural Development

Evidence from neuroscience indicates that EFs are mediated primarily by the most anterior region of the brain—the prefrontal cortex. The prefrontal cortex shows notable changes from early childhood through adolescence and does not appear to reach full maturity until age 25 (O'Hare & Sowell, 2008). While a full consideration of the neural correlates of each of the EFs is beyond the scope of this article, some general points are noteworthy. The timing of rapid change and age of full maturity vary by EF component (Best & Miller, 2010). This variation includes differences in the developmental trajectories of EFs, where one function, such as working memory, reaches adult-like levels by 12 years of age, whereas another—cognitive flexibility—continues to develop until 15 years of age (Huizinga et al., 2006).

Development in EFs links to structural changes as well as functional shifts in organization, including changes in neural networks, localization, and integration (Casey et al., 2005). Such changes in the brain and in task performance do not necessarily correspond directly. While changes in task performance may be barely detectable, what is happening at the neural level can be dramatic. For instance, young children can complete inhibition tasks, but they use more of their brains to do so—that is, more areas of the brain are activated than when they are older (Durston et al., 2006). As such, developmental differences may show up in efficiency and effort, rather than in accuracy measures (Best & Miller, 2010).

EFs emerge early in life, with periods of rapid development in the preschool years and again from ages 5 to 8 years (for reviews, see Best & Miller, 2010; Lee, Bull, & Ho, 2013). Marked changes, particularly in the higher-order EFs, are also evident in late childhood and into adolescence (Huizinga et al., 2006). Brain changes in adolescence are driven in part by increased myelination, neuron proliferation, and synaptic pruning (Casey et al., 2005; O'Hare & Sowell, 2008). Efficiency increases in adolescence, but so does differentiation among the core EFs (Lee et al., 2013; Miyake et al., 2000). Furthermore, as specific EFs mature, other more advanced skills are recruited to complete tasks (Chevalier, Martis, Curran, & Munakata, 2015).

In sum, understanding the developmental trajectory of different EFs not only advances science, but it also yields practical implications that enable tailoring assessments and interventions to meet students' developmental level.

Measuring EFs

For research on EFs to be educationally useful, measurement must be meaningful for both diagnostic and evaluation purposes. Measuring EFs is challenging. Most tasks require a combination of working memory, inhibition, and cognitive flexibility, so any attempt to isolate one EF component in performance on a specific task is almost impossible (Miyake et al., 2000). Furthermore, findings from different tasks designed to measure the same skills are inconsistent. Even the same task used repeatedly does not show consistent performance because EFs are frequently applied in novel situations, and a task can only be novel on the first administration.

In early childhood, rating scales completed by parents and teachers are the most ecologically valid measures of EFs. Rating scales provide information about how children regularly behave during activities typical in home and school life. A common tool is the Behavioral Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000). The BRIEF contains 86 ratings that load into different factors (e.g., "Acts wilder or sillier than others in groups" loads [negatively] onto the inhibitory factor). Some drawbacks to this rating approach include the difficulty of isolating a single EF, given that in ecologically valid contexts, components overlap. In addition, observed behaviors could reflect several contributing factors difficult to isolate from EFs. Rating scales are also subject to bias, given the emotional connections between caretakers and the children they are rating.

Laboratory-based tasks avoid bias and often aim to measure one aspect of EF, although no measure is pure. Laboratory tasks of inhibition include both attentional and behavioral inhibition. An example of a behavioral inhibition task is the Go/No-go task: Instructed to respond to only one stimulus, children watch a display in which one of two stimuli briefly appear. The "go" stimuli outnumber the "no-go" stimuli typically 4-1, creating a bias to "go" that must be inhibited on "no-go" trials.

Inhibition of attention is commonly measured with flanker or Stroop tasks (Eriksen, 1995; Stroop, 1935). The flanker task requires attention to a centrally located stimulus (an arrow or fish) while ignoring distractors on either side, "flanking" the target stimulus (Zelazo et al., 2013). The orientation of the flanking stimulus can be either congruent (facing the same direction) or incongruent (facing the opposite direction) to the central stimulus. Another task—the Color-Word Stroop—requires individuals to resist reading the color word, and instead name the color of the ink in which that word is printed (e.g., the word "blue" printed in red ink). Commonly used to assess inhibition in adolescents and adults, the reading requirements of the classic Stroop task make it inappropriate for use with young children (Esposito, Baker-Ward, & Mueller, 2013; Stroop, 1935). The Bivalent Shape Task is an alternative that does not require reading, as the goal is to match on shape and inhibit reaction to a highly salient color. In both the Flanker and Bivalent Shape tasks, incongruent trials measure inhibition. Inhibition tasks administered on computers are useful, as they enable researchers to assess older children and adolescents using efficiency scores that consider performance on multiple trials, along with precise measurements of response time (Esposito et al., 2013).

The working memory component of EFs is best measured with tasks that require mental manipulation (Diamond, 2013). An example is the List Sorting Working Memory task in the NIH Toolbox Cognition Battery (Tulsky et al., 2013). In this task, pictures of either animals or foods appear one at a time on a screen in increasingly longer sequences, and children are instructed to repeat them back in size order. In the final block, children must first report foods and then animals, both in size order, requiring extensive mental manipulation.

Cognitive flexibility (or mental-set shifting) is commonly measured with tasks that require flexibly applying rules or switching rule sets, such as the Dimensional Change Card Sort (Zelazo et al., 2013). Children first sort a set of bivalent pictures (such as trucks and rabbits depicted in red or blue) by one dimension (color or shape), and then switch to the other dimension. Young children can sort by the first dimension but fail to switch rule sets even though they can correctly verbalize the new rule (Zelazo et al., 2013). Although accuracy reaches ceiling in childhood even on the complex versions, sorting reaction times vary, and the switch is cognitively difficult throughout development (Diamond & Kirkham, 2005).

Higher-order EFs have received less attention in the measurement of normative development. That being said, planning is often measured using the Tower of Hanoi task (Welsh, 1991). Individuals see a picture of three rings arranged on three prongs and must arrange the rings to match the picture in as few moves as possible. Moves are constrained by two rules: Only one ring can be moved at a time, and a bigger ring cannot be placed on top of a smaller one. This task measures future-oriented planning or children's ability to inhibit the tendency to move the disks straight to the end goal location, which would require breaking the ground rules.

Best practice in measuring EFs uses several tasks matched to developmental ability. Task-performance accuracy typically reaches ceiling in the window between preschool and early elementary school. Response time continues to improve until maturity toward the end of adolescence. Thus, laboratory tasks with preschool-aged children typically measure accuracy of response. Response time—or efficiency scores that consider both accuracy and response time—are implemented when accuracy alone is no longer informative, namely in older children and adolescents (Diamond & Kirkham, 2005).

Assessing the Importance of EFs in School Achievement

EFs consistently correlate with academic performance (Best et al., 2011; Diamond, 2013; St. Clair-Thompson & Gathercole, 2006). During the early years, EFs predict school readiness and achievement better than IQ does (Blair & Razza, 2007). Furthermore, teachers report EFs as the most important determinants of success in the classroom, and teacher ratings of attention, working memory, and inhibitory control predict both literacy and math achievement from kindergarten to sixth grade (McClelland et al., 2007). EFs matter long after school entry—their influence is maintained through elementary school and into middle and high school (Best et al., 2011). Concurrent associations between academic performance and EFs are robust with different measurement methods and, across different academic domains, including reading, math, and science (for a review, see Jacob & Parkinson, 2015).

Although correlations between EFs and academic achievement are evident across development and methods, the relationship is typically moderate. The strongest evidence for links with achievement outcomes is for working memory and inhibition, with far less consistent evidence for relations with cognitive flexibility (Blair & Razza, 2007; St. Clair-Thompson & Gathercole, 2006). Findings from longitudinal studies linking EFs and achievement outcomes are consistent with the studies showing concurrent associations (Jacob & Parkinson, 2015); however, when studies include relevant control measures, such as children's background characteristics and IQ, the correlation is not always present (Willoughby, Kupersmidt, & Voegler-Lee, 2012). Associations between EFs and academic outcomes may be bidirectional, and school entry itself may contribute to the rapid development of EFs during early elementary years (McCrea, Mueller, & Parrila, 1999). The empirical evidence for causal links is slim, and few studies demonstrate that exposure to an intervention yields changes in EFs that improve achievement outcomes (Jacob & Parkinson, 2015). Granted, the lack of evidence could be due to an absence of empirical studies or to non-significant findings.

The Malleability of EFs: Constraining and Promoting Environments

EFs are subject to environmental influence, both positively and negatively. Children growing up in poverty perform less well on tasks assessing EFs than those growing up in households reporting higher incomes (Moffitt et al., 2011). Children growing up in poverty are more likely than their more advantaged peers to be sleep deprived, under stress, and in poor physical health. All these risk factors potentially affect cognitive development, sometimes manifesting as poor EFs (Kishiyama, Boyce, Jimenez, Perry, & Knight, 2009).

Proximal environments also afford opportunities to develop EFs through the provision of particular activities. In one study, opportunities to engage in less-structured leisure time, such as child-directed play, yielded better self-directed executive functioning than participation in structured lessons (Barker et al., 2014). The cross-cultural work on EFs suggests that cultural differences in classroom interaction structures may influence the development of EFs. Observed strengths in EFs among Chinese preschoolers, for example, may be attributable to socialization experiences that promote inhibitory self-control (Lan, Legare, Ponitz, Li, & Morrison, 2011).

Other studies also show that having to navigate different language environments can confer benefit, suggesting a possible "bilingual advantage" in EFs (Adesope, Lavin, Thompson, & Ungerleider, 2010). For example, after controlling for socioeconomic status, bilingual children outperformed monolingual peers on a number of EF tasks (Carlson & Meltzoff, 2008). However, kindergarten children showed no advantage from a dual-language education program, supporting second-language fluency only in school. Participating in dual-language education programs may yield EF benefits with more (5+) years of enrollment (Bialystok & Barac, 2012), suggesting a dose–response relation between bilingual education and EFs. Still, other studies fail to find a benefit in EFs related to bilingualism (see a review by Valian, 2015). Thus, although second-language exposure might confer EF benefits, the circumstances under which they do remain unclear.

EFs as a Viable Target for Intervention in Schools

Intervention research highlights the emergence of three seemingly disparate approaches to enhancing EFs: curriculum-based activities, physical exercise, and computer-based cognitive training. Interventions vary in the cognitive skills they target for improvement, and whether the target is a broad process (e.g., self-regulation) or narrower specific skills (working memory) or strategies (problem solving). Interventions also differ based on the targeted age group and delivery context. In school contexts, curriculum-based approaches target younger children, whereas in out-of-school contexts, computer-based training and exercise target individuals across the life span from early childhood to late adulthood. Nonetheless, the different intervention approaches all emphasize active engagement in effortful activities, to counter sub-optimal functioning resulting from impairment (e.g., attention-deficit hyperactivity disorder [ADHD]), poor physical health, stress, or impoverished environments. A key feature of all intervention methods that confer EF benefits is an opportunity to repeatedly practice at progressively advanced levels (Diamond & Ling, 2016).

Evidence-based examples of curriculum-based interventions include *Tools of the Mind* and PK-*PATHS* (Promoting Alternative Thinking Strategies) curriculum, and the social emotional training component of the Head Start Research-Based Developmentally Informed program (REDI; Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008). These curricula generally target more than EFs, and perhaps because of this, tend to be more efficacious than interventions that are more narrowly focused (Diamond & Ling, 2016). The *Tools of the Mind* curriculum was designed to promote young children's acquisition of literacy, math, and self-regulatory skills through EF-enhancing activities, such as planning through self-speech, collaborative dramatic play with peers, and shared activities with teachers (Bodrova & Leong, 2007). Students exposed to *Tools* were rated by teachers at the end of the school year as exhibiting fewer behavior problems than children in control classrooms (Barnett et al., 2008). Children receiving *Tools* showed significant gains in EFs, compared with children receiving an academic intervention (Diamond, Barnett, Thomas, & Munro, 2007). A randomized-controlled study showed several positive outcomes among students exposed to *Tools*, including improvements in EFs, reading, vocabulary, and mathematics (Blair & Raver, 2014). However, some studies testing *Tools* have not yielded improvements in EFs or related behavior, although inconsistencies in findings may be explained by differences in intervention duration, or whether a component or the full curriculum was implemented (Diamond & Ling, 2016).

Although still in its infancy, some research tests physical activity as an intervention (Best, 2010; Diamond, 2015). Two intervention studies conducted with children support cognitively engaging physical activity, as opposed to simple activities such as riding a stationary bike. An experiment randomly assigned children to participate in Tae Kwon Do, showed gains in all EFs assessed, compared with a control group participating in a simple physical activity (Lakes & Hoyt, 2004). Non-competitive sports game participation among school-age children with obesity showed a dose response (Davis et al., 2011). Children participating for 40 min per day showed improvements in both EFs and math performance, even without specific training in either. Given the correlates of poor EF—a lack of physical fitness, sadness, and stress—participating in physical activities may affect EFs by ameliorating risk factors (Best, 2010; Diamond, 2015).

Perhaps the most visible approach to building EFs is computer-based cognitive training. Programs have been applied across development from early childhood to older adulthood. Examples of programs that target children and have been empirically tested include CogMed and Learning RX. Delivery contexts vary: Some programs, such as Learning RX, are delivered one on one with a human trainer, others are administered in small groups, but most are delivered in an individualized context via adaptive computer software. Often called "brain games," cognitive training is not entirely like playing computer games. Cognitive training programs generally use a set of standardized tasks that are "repurposed" cognitive tasks initially developed by psychologists as tests of mental abilities. The tasks typically target specific skills, usually working memory. Tasks are generally adaptive, such that as trainees gain mastery, tasks become progressively harder and the speed at which they must complete tasks shortens.

Several meta-analytic reviews quantify associations between cognitive training and outcomes. Short-term, modest improvements, particularly in working memory, result from training; effects are generally robust but only for performance on cognitive tasks like the one that was trained. The evidence for positive effects of cognitive training is stronger for young children and older children with specific cognitive deficits, such as those with ADHD (e.g., Klingberg et al., 2005; Shalev, Tsal, & Mevorach, 2007). However, advertising notwithstanding, cognitive training will not "cure" ADHD, and caution is exercised given a number of studies that show no effect of training, and the clear need for more research (Shipstead, Redick, Engle, & Hinshaw, 2012).

The training context matters: Studies of computer-based cognitive training are frequently conducted in highly controlled research settings, and assessing effectiveness is difficult, without implementing these interventions in the "real world," such as in schools with teachers in charge of administration (Hill, Serpell, & Faison, 2016). Whether cognitive training programs transfer to areas other than the one trained is not well established. A few studies with school-aged participants demonstrate transfer to measures of fluid intelligence (Chein & Morrison, 2010; García-Madruga et al., 2013; Hill et al., 2016; Klingberg et al., 2005). Some limited evidence suggests that cognitive training improves children's performance in math (Holmes, Gathercole, & Dunning, 2009) and reading (García-Madruga et al., 2013; Loosli, Buschkuehl, Perrig, & Jaeggi, 2012).

Research Conclusions

The consistent moderate association between EFs, classroom performance, and long-term outcomes underscores the role EFs may have for learning. Indeed, EFs are critical to the skills needed for success in the 21st century (Diamond, 2013). What we draw from the science is that EFs are malleable, environments are important for supporting their development, they have long-term implications for children's educational outcomes, and some evidence suggests that varied approaches can improve EFs. However, we know less about whether any observed gains in behavioral measures or performance on EF tasks that result from intervention are linked to neural changes, nor whether positive effects maintain over time.

Key points from the EF interventions: Children who are most "at-risk" benefit the most, tasks need to be challenging and include attention to social/emotional skills, evidence supports near transfer (especially when tasks are similar to the training protocol), but evidence of far transfer to academic achievement is, at best, promising. A remaining question is whether these interventions are worth the time and monetary investment, especially given the problem of transfer. Based on the science thus far, deficits in EFs are not intractable, and in fact interventions most benefit the students with the poorest skills. Furthermore, brain development does not stop at preschool, and learning environments can capitalize on this potential for continued growth in EFs.

Policy Implications

Policy implications must consider the current educational climate. No Child Left Behind and the Every Student Succeeds Act encouraged a shift toward academic subjects to ensure proficient performance in high-stakes tests, and this reduced arts programing and physical activity in the schools. The Association of American Educators reports that the scaling back over the last decade of these activities hits schools in low-income urban districts and elementary schools the hardest. To encourage the development of EFs, the activities known to support their development should appear in school curriculum to ensure that all children have access, regardless of economic resources.

Knowing which activities foster the development of EFs can help direct school programing. The question of what constitutes the "known" may be debated, but our review suggests that existing interventions targeting EFs that have been explored thus far—curricula, physical activity, and computer-based training—can be implemented in schools and likely at relatively low cost (Diamond & Ling, 2016). Specific implications for educational practice are preliminary, but providing opportunities for semi-structured peer play and scaffolding of inhibitory control may enable EF-related skills. Participation in structured physical activities, particularly those that promote self-regulatory skills and are cognitively enriching, is likely to support EFs. Computer-based learning environments that support challenging and adaptive practice of basic EFs such as working memory and higher-order cognitive skills, such as problem solving or planning, also have potential.

Using physical activity or computer-based training of basic cognitive skills must first consider whether time spent training might not be better spent on more enriching educational activities. We advocate some creative thinking in this area. The best approach to cognitive training is to provide it in the context of a richer set of activities that are enjoyable, emotionally fulfilling, and potentially social (Diamond, 2015). Approaches can also be combined to use EF training and typical educational activities in tandem. For example, technological advances can support more engaging and socially mediated training programs, and integrate training with content-based activities that in the end may help solve the transfer problem (Deveau, Jaeggi, Zordan, Phung, & Seitz, 2014).

EFs are a critical point of intervention for children placed at risk by growing up in impoverished environments. The majority of environmental conditions associated with higher EFs are also more likely to be present in families and schools with greater resources. For example, the new digital divide lies less with access to technology but more with access to software (Warschauer & Matuchniak, 2010). Poorly resourced schools are often using computers for drill and skill activities in math and spelling as opposed to more complex learning environments, where children have to bring to bear higher-order planning and problem-solving EFs.

Some environments constrain the development of EFs, and some learning environments support their development. Schools can provide opportunities for children to develop EFs that might not otherwise be available to all families. Expanding the role of schools, particularly at the elementary and middle school levels, may be helpful. The current focus on content-based learning, test taking, and academic performance, neglects a broader goal—supporting cognitive development. Enabling schools to identify, select, and implement evidence-based programs that foster the development of EFs is therefore critically important. EFs can be developed not only in the service of learning in school but also in their own right as a dimension to all of life's work. That said, translating the scientific research to the real contexts in which education takes place will require teacher training that bridges a substantial knowledge and application gap.

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