REVIEW

Interventions Shown to Aid Executive Function Development in Children 4 to 12 Years Old

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To be successful takes creativity, flexibility, self-control, and discipline. Central to all those are executive functions, including mentally playing with ideas, giving a considered rather than an impulsive response, and staying focused. Diverse activities have been shown to improve children's executive functions: computerized training, noncomputerized games, aerobics, martial arts, yoga, mindfulness, and school curricula. All successful programs involve repeated practice and progressively increase the challenge to executive functions. Children with worse executive functions benefit most from these activities; thus, early executive-function training may avert widening achievement gaps later. To improve executive functions, focusing narrowly on them may not be as effective as also addressing emotional and social development (as do curricula that improve executive functions) and physical development (shown by positive effects of aerobics, martial arts, and yoga).

What will children need to be successful? What programs are successfully helping children develop those skills in the earliest school years? What do those programs have in common?

Four of the qualities that will probably be key to success are creativity, flexibility, self-control, and discipline. Children will need to think creatively to devise solutions never considered before. They will need working memory to mentally work with masses of data and see new connections among elements, flexibility to appreciate different perspectives and take advantage of serendipity, and self-control to resist temptations and avoid doing something they would regret. Tomorrow's leaders will need the discipline to stay focused, seeing tasks through to completion.

All of those qualities are executive functions (EFs), the cognitive control functions needed when you have to concentrate and think, when acting on your initial impulse might be ill-advised. EFs depend on a neural circuit in which the prefrontal cortex is central. Core EFs are cognitive flexibility, inhibition (self-control, self-regulation), and working memory (*1*). More complex EFs include problem-solving, reasoning, and planning. EFs are more important for school readiness than is intelligence quotient (IQ) (*2*). They continue to predict math and reading competence throughout all school years [e.g., (*3*)]. Clearly, to improve school readiness and academic success, targeting EFs is crucial. EFs remain critical for success throughout life [in career (*4*) and marriage (*5*)] and for positive mental and physical health (*6*, *7*).

Children with worse self-control (less persistence, more impulsivity, and poorer attention regulation) at ages 3 to 11 tend to have worse health, earn less, and commit more crimes 30 years later than those with better self-control as children, controlling for IQ, gender, social class, and more (*8*). Since "self-control's effects follow a [linear] gradient, interventions that achieve even small improvements in self-control for individuals could shift the entire distribution of outcomes in a salutary direction and yield large improvements in health, wealth, and crime rate for a nation" (*8*).

What Programs Have Been Shown to Help Young Children Develop These Skills?

There is scientific evidence supporting six approaches for improving EFs in the early school years. Tables S1 and S2 provide details on each intervention and their outcomes.

Computerized training. The most researched approach, and one repeatedly found successful, is CogMed (Pearson Education, Upper Saddle River, NJ) computerized working-memory training (*9*–*13*), which uses computer games that progressively increase working-memory demands. Youngsters improve on games they practice (Fig. 1), and this transfers to other working-memory tasks. Groups studied have been typically developing children (*12*) and those with attention deficit hyperactivity disorder (ADHD) (*10*, *13*) or poor working-memory spans (*9*). Benefits usually do not generalize to unpracticed EF skills (*14*). Three studies (*9*–*11*) included controls who played the same training games without increasing difficulty; those controls did not show the same gains. Two studies looked 6 months later and found EF benefits remained (*9*, *13*). For math, gains were

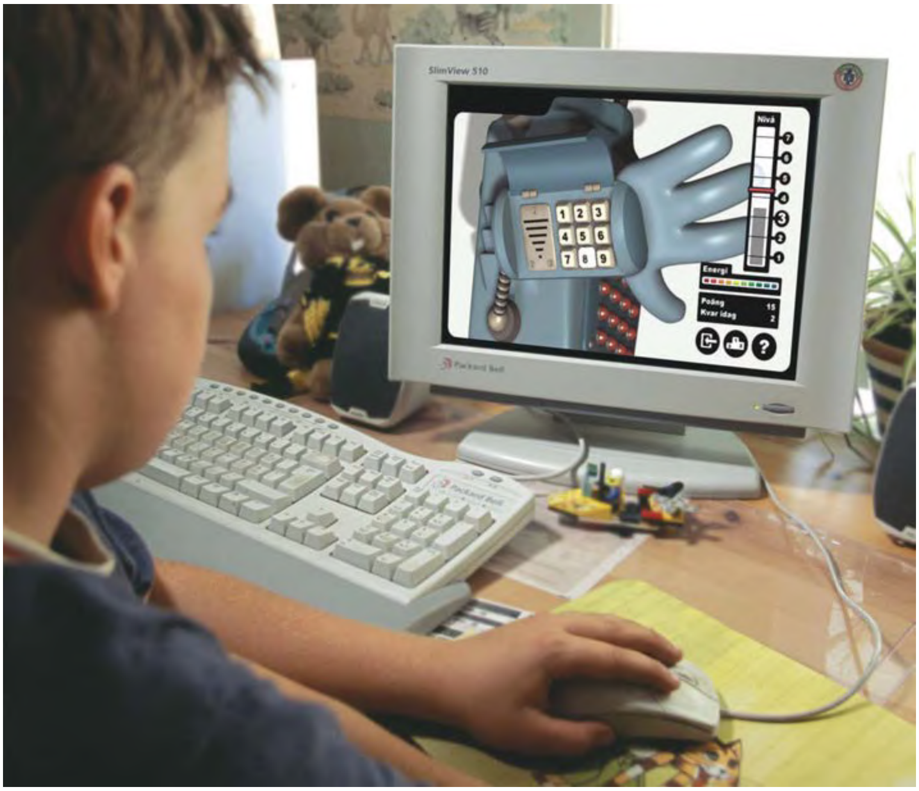

Fig. 1. A teen working at a CogMed game. [Photo courtesy of CogMed]

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not evident immediately but were evident 6 months later (*9*).

In a double-blind, randomized-control trial with multiple training and transfer tasks, one group of 4-year-olds was trained on working memory (using CogMed), one on nonverbal reasoning, another on both, and a control group on both but remaining at the easiest level. Those trained on working memory improved more on working-memory transfer tasks than did controls, and those trained in reasoning improved more on reasoning transfer tasks than controls (*11*). Neither group showed transfer to the unpracticed skill (reasoning for the former, working memory for the later). The combined group showed less improvement on both (having received less practice on each). Transfers were narrow. Nonverbal analogical-reasoning training transferred to nonverbal analogical reasoning on Raven's Matrices but not to nonverbal gestalt completion on Raven's. Nonverbal working-memory training transferred to other measures of nonverbal working memory but not to the one measure of verbal working memory.

Efforts to use computer games to train inhibition have experienced limited success. Using the same dosage, duration, and frequency as CogMed studies, Thorell *et al*. found improvements in 4- and 6-year-olds on only two of the three inhibition games practiced, with no transfers to unpracticed tasks (*12*). Perhaps the children were too young, training too brief, or training tasks not optimal.

After training with computer games that taxed working memory and/or inhibitory control (gradually increasing in difficulty) or that required visuomotor control, 4- and 6-year-olds showed no cognitive benefits save one (*15*)—improved matrices score (reasoning) on the Kaufman Brief Intelligence Test (K-Bit)—nor did their parents report better EFs. However, more mature brain-electrical responses during a selective-attention task were found after training (perhaps presaging later cognitive advances).

Hybrid of computer and noncomputer games. When children of 7 to 9 years were randomly assigned to reasoning or speed training with computerized and noncomputerized games (played individually and in small groups, with difficulty incrementing), improvements transferred to untrained measures of each but were specific (*16*). Those trained on reasoning did not improve on speed, and those trained on speed did not improve on reasoning relative to baseline.

Aerobic exercise. Aerobic exercise robustly improves prefrontal cortex function and EFs (*17*, *18*). Although most studies have involved adults and/or examined effects of a single bout of aerobic exercise, which may be transient, this conclusion has support in three studies of sustained exercise in children.

Aerobic running (with exercises becoming more demanding over time) improved 8- to 12-year-olds' cognitive flexibility and creativity, and significantly more so than did standard physical education, yet did not affect non-EF skills (*19*).

Davis *et al*. (*20*) randomly assigned sedentary, overweight 7- to 11-year-olds to no treatment, 20 min/day or 40 min/day of group aerobic games (running games, jump rope, basketball, and soccer), with an emphasis on enjoyment and intensity, not competition or skill enhancement. Only the high-dose aerobics group improved on EFs (only on the most EF-demanding measure) and math, compared with no-treatment controls. Dose-response benefits of aerobic exercise were found for the most difficult EF task and for math. Neither aerobics group improved more than controls on the EF skill of selective attention or on non-EF skills.

When 7- to 9-year-olds were randomly assigned to 2 hours of fitness training daily for the school year (aerobic activities for 70 min, then motor skill development) or no treatment, those who received fitness training showed more improvement in working memory than did controls, which was especially evident when working-memory demands were greater (*21*). However, working memory did not differ significantly between the two groups at either pre- or posttest.

Suggestive evidence from studies of physical activity (*22*, *23*) and music training (*24*, *25*) indicates that exercising bimanual coordination may improve EFs. So far evidence shows no EF benefits from resistance training (*26*, *27*). There are not yet studies of the benefits of sports for EFs to our knowledge. Sports might benefit EFs more than aerobic exercise alone because, besides improving fitness, sports challenge EFs (requiring sustained attention, working memory, and disciplined action) and bring joy, pride, and social bonding [it is known that sadness, stress, and loneliness impair EFs (see final paragraph)].

Martial arts and mindfulness practices. Traditional martial arts emphasize self-control, discipline (inhibitory control), and character development. Children getting traditional tae-kwon-do training (Fig. 2) were found to show greater gains than children in standard physical education on all dimensions of EFs studied [e.g., cognitive (distractible-focused) and affective (quitting-persevering)] (*28*). This generalized to multiple contexts and was found on multiple measures. They also improved more on mental math (which requires working memory). Gains were greatest for the oldest children (grades 4 and 5), least for the youngest [kindergarten (K) and grade 1], and greater for boys than girls. This was found in a study where children 5 to 11 years old were randomly assigned by homeroom class to tae-kwon-do (with challenge incrementing) or standard physical education. Besides including physical exercise, martial-arts sessions began with three questions emphasizing self-monitoring and planning: Where am I (i.e., focus on the present moment)? What am I doing? What should I be doing? The later two questions directed children to select specific behaviors, compare their behavior to their goal, and make concrete plans for improvement. Unlike many studies that target disadvantaged children and/or those behind on EFs, children in this study were socioeconomically advantaged, making the findings especially impressive.

Fig. 2. A child demonstrating a tae-kwon-do stance. [Photo credit: Haiou Yang]

Instructive findings are also reported in a study with adolescent juvenile delinquents (*29*). One group was assigned to traditional tae-kwon-do (emphasizing qualities such as respect, humility, responsibility, perseverance, and honor, as well as physical conditioning and focusing on self-control and self-defense). Another group was assigned to modern martial arts (martial arts as a competitive sport). Those in traditional tae-kwon-do showed less aggression and anxiety and improved in social ability and self-esteem. Those in modern martial arts showed more juvenile delinquency and aggressiveness and decreased self-esteem and social ability.

In one study, mindfulness training sessions consisted of three parts: sitting meditation; activities to promote sensory awareness, attention regulation, or awareness of others or the environment; and a body scan. Demands on mindfulness increased over time as the first and third parts lengthened and the more goal-directed and less-reflective middle portion became briefer. Skills practiced in parts 1 and 3 involved top-down control of attention [bringing attention to the present moment, noticing when attention had wandered (monitoring), and bringing it back nonjudgmentally to the intended target]. After mindfulness training, greater EF improvements were found in 7- to 9-year-olds with initially poorer EFs than those with initially better EFs compared with controls (who silently read instead) (*30*). Children with initially poor EFs showed EF improvements overall and in the components of shifting and monitoring, bringing their scores up to average. Both teachers and parents reported these improvements, suggesting that they generalized across contexts.

There is some suggestion that yoga might help as well. Girls 10 and 13 years old were randomly assigned to yoga or physical training (*31*). Yoga training (physical training, relaxation, and sensory awareness) improved EFs, with improvements most evident when EF demands were greatest. Physical training (physical activity without mindfulness) produced no EF improvement.

Classroom curricula. Two curricula that share important similarities have been shown to improve EFs (*32*). *Tools of the Mind* (*Tools*) is a curriculum for preschool and kindergarten developed by Bodrova and Leong (*33*) based on work by Vygotsky (*34*). Vygotsky emphasized the importance of social pretend play for the early development of EFs. During pretend play, children must inhibit acting out of character, remember their own and others' roles, and flexibly adjust as their friends improvise. Such play exercises all three core EFs and is central to *Tools*. Children plan who they will be in a pretend scenario, and the teacher holds them accountable for following through. Bodrova and Leong initially tried *Tools* as an add-on to existing curricula. Children improved on what they practiced in those modules, but benefits did not generalize. For benefits to generalize, supports, training, and challenges to EFs had to be part of what children did all day at school and therefore are now interwoven into all academic activities.

Children are taught how to support nascent EFs by scaffolding with visual reminders (e.g., a drawing of an ear to remember to listen) and private speech. Instead of being embarrassed for being poor listeners, the simple drawing of an ear enables children to proudly be good listeners. As EFs improve, supports are gradually removed, gently pushing children to extend the limits of what they can do.

Tools was evaluated against another high-quality program by using EF measures that required transfer of training (*35*). *Tools* 5-year-olds outperformed control children on both EF measures (which taxed all three core EFs), especially on the more EF-demanding conditions. Thus, the program with more play produced better EFs than the one with more direct instruction. One school was so impressed by how much better *Tools* children were doing that it withdrew from the study and switched all classes to *Tools*.

Montessori (*36*) curriculum does not mention EFs, but what Montessorians mean by "normalization" includes having good EFs. Normalization is a shift from disorder, impulsivity, and inattention to self-discipline, independence, orderliness, and peacefulness (*37*). Montessori classrooms have only one of any material, so children learn to wait until another child is finished. Several Montessori activities are essentially walking meditation (Fig. 3).

Fig. 3. Walking meditation in Montessori can be simply walking on a line (which required focused attention and concentration for young children) or walking on it without spilling water in a spoon or without letting your bell ring. [Photo credit: K. L. Campbell for Cornerstone Montessori School]

As in *Tools*, the teacher carefully observes each child (when a child is ready for a new challenge, the teacher presents one), and whole-group activities are infrequent; learning is hands-on, often with ≥2 children working together. In *Tools*, children take turns instructing or checking one another. Cross-age tutoring occurs in Montessori mixed 3-year age groups. Such child-to-child teaching has been found repeatedly to produce better (often dramatically better) outcomes than teacher-led instruction (*38*–*40*).

Children chosen by lottery to enter a Montessori public school approved by the Association Montessori Internationale (AMI) were compared to those also in the lottery but not chosen, at the end of kindergarten (age 5) and the end of grade 6 (age 12) (*41*). At age 5, Montessori children showed better EFs than peers attending other schools. They performed better in reading and math and showed more concern for fairness and justice. No group difference was found in delay of gratification. At age 12, on the only measure related to EFs, Montessori children showed more creativity in essay writing than controls. They also reported feeling more of a sense of community at school.

Add-Ons to Classroom Curricula (*32*). Two programs with different philosophies, both intended to complement existing curricula, improve EFs (*32*). PATHS (*42*) (Promoting Alternative Thinking Strategies) trains teachers to build children's competencies in self-control, recognizing and managing feelings, and interpersonal problem-solving. Young children experience and react to emotions before they can verbalize them and often react impulsively without top-down control. Thus, training in verbalizing one's feelings and practicing conscious self-control strategies (e.g., waiting before acting and self-talk) are emphasized. When children get upset, they should stop, take a deep breath, say what the problem is and how they feel, and construct an action plan. Teachers are taught techniques to generalize skills learned during PATHS lessons to other contexts during the school day. After a year of PATHS, 7- to 9-year-olds showed better inhibitory control and cognitive flexibility than control children (*43*). Children who showed greater inhibitory control at posttest showed fewer internalizing or externalizing behavior problems 1 year later.

Using a different approach, the Chicago School Readiness Project (CSRP) provided Head Start teachers with extensive behavior-management training and suggestions for reducing their stress. Strategies taught were similar to those

Table 1. Comparison of curricula and curricula add-ons. (The "Montessori" name is not copyrighted; anyone can claim their school is a Montessori school. The features listed below usually characterize high-quality Montessori programs, especially each child freely choosing what to work on and where (the floor, at a table, or outside the room) while the teacher observes each child's activities, challenging and helping each to progress. Morning and afternoon sessions are free of scheduled activities, so children can work uninterrupted. Curiosity and interest are valued over finding single answers. The walls are uncluttered; the environment simple but attractive. There is a calm and peaceful atmosphere, with most children in deep concentration on their activities. Large class size is no problem; indeed, classes of 30 to 40 are preferred over classes of 15 to 20 because only when the teacher:child ratio is sufficiently large do older children perceive the need to help instruct younger ones, and such child-to-child mentoring is greatly valued.)

Program	Tools of the Mind	Montessori	PATHS	CSRP
Developed by	Bodrova and Leong (*33*)	Montessori (*37*)	Kusché and Greenberg (*43*)	Raver (*47*)
Based on	Vygotsky (*34*)	Montessori (*37*)	Affective-Behavioral-Cognitive-Dynamic (ABCD) model (*7*)	Incredible Years (*46*)
For age (years) and grades	(3–6) Preschool and K	(0–18) Infancy to grade 12	(3–12) Preschool to grade 6	3–5 (Preschool)
Academic content	Yes; a complete curriculum	Yes; a complete curriculum	None	None
Socioemotional content	Yes	Yes	Yes	Yes
EFs challenged all day	Yes	Yes	Yes	No
Connects cognitive, social, and emotional development	Yes	Yes	Yes	Yes
Particular focus on oral language development	Yes	Yes	Yes	No
Self-talk (private speech) encouraged in children	Yes	Yes	Yes	No
Scaffolds (supports) so children succeed	Yes	Yes	Yes	Yes
Reprimand frequency	Rare	Virtually never	Rare	Rare
Extrinsic rewards used	No	No	No	Yes
Planning by child is emphasized	Yes	Yes	Yes (but not in preschool)	No
Individualized pacing and instruction	Yes	Yes, pronouncedly so	No	No
Child-to-child tutoring	Take turns as doer and checker	Cross-age tutoring	No	No
Teacher as scientist and observer (dynamic assessment)	Yes	Yes	No	No
Teacher training	12 days of workshops over 2 years; 12 days of in-classroom follow up	1 to 2 years full-time plus in-service refreshers	2 days of workshops; classroom observations for 30 min/week for 30 weeks	12 days over 20 weeks; 30 hours of workshops; 4 hours/week for 20 weeks of mentoring
Play is given a prominent role	Yes; especially social dramatic play	Playfulness, creativity encouraged; but rather than play at activities like cooking, children cook; no social dramatic play	Play in preschool and K only	No
Active, hands-on learning even preschoolers work in groups of 2 or 3, or alone*	Yes	Yes	Somewhat in preschool and K, but not later	No
Character development (kindness, helpfulness, empathy) emphasized	Yes	Yes	Yes	Yes
Labeling and identifying feelings emphasized	Somewhat	No	Yes, high priority	Yes
Awards and honors received	An Exemplary Innovation, International Bureau of Education of UNESCO	The widest geographical spread of any education program. Currently in 117 countries across six continents	Seven awards and honors†	

*This is in contrast to "whole-group," where the teacher teaches the whole class together; children are expected to sit quietly, sometimes for extended periods. †Awards and commendations received by the PATHS program: Model Program (Blueprints Project for the Center for the Study and Prevention of Violence, University of Colorado); Model Program (KidsMatter Australian Primary Schools Mental Health Initiative); Highly Rated Program (Substance Abuse and Mental Health Services Administration's National Registry of Evidence-Based Programs and Practices); Best Practices Program (Centers for Disease Control and Prevention); Promising Program (U.S. Department of Education, Safe and Drug-Free Schools); and Promising Program (U.S. Surgeon General's Report on Youth Violence) in *Incredible Years* (*44*) (e.g., implement clearer rules and routines, reward positive behavior, and redirect negative behavior). CSRP intentionally did not train teachers in academic instruction or provide curricula on academic subjects. It emphasized developing verbally skilled strategies for emotion regulation. Mental health consultants conducted stress-reduction workshops for teachers all year. Children with the worst externalizing behavior received one-on-one counseling.

Raver, who directs CSRP, headed a randomized-control trial (*45*, *46*) with 18 of 35 Head Start classrooms assigned to CSRP. CSRP teachers provided better-managed and more emotionally supportive classrooms than those of control teachers. EFs (attention, inhibition, and experimenter-rated impulsivity) of 4-year-olds in CSRP classes improved over the year and significantly more so than did EFs of controls. CSRP did not affect delay of gratification, however. CSRP children improved in vocabulary, letter naming, and math significantly more than did controls. CSRP's improvement of academic skills was mediated largely via its improvement of EFs. EFs in the spring of preschool predicted achievement 3 years later in math and reading (*47*).

What Lessons Can Be Learned About What Aids EF Development in Young Children from These Six Approaches?

1) Those with the initially poorest EFs gain the most. Lower-income, lower-working-memory span, and ADHD children, and, in one study, boys [who often have poorer inhibitory control than girls (*8*)] generally show the most EF improvement from any program. Early EF training is thus an excellent candidate for leveling the playing field and reducing the achievement gap (*48*) between more- and less-advantaged children. EFs predict later academic performance (*3*), so, as go EFs, so goes school readiness and academic achievement.

2) The largest differences between those in programs that improve EFs and control participants are consistently found on the most demanding EF measures. Everyone does fine when EF demands are low. Group differences are clearest when substantial executive control is needed.

3) EFs must be continually challenged to see improvements. Groups assigned to the same program, but without difficulty increasing, do not show EF gains.

4) Studies of curricula (*35*, *41*) and curricula add-ons (*43*, *45*, *46*) demonstrate that EFs can be improved, even at 4 to 5 years of age, by regular teachers (given training and support) in regular classrooms without expensive equipment.

5) There are suggestions that computer training (*9*–*13*) and martial arts (*28*) may benefit children of 8 to 12 more than children of 4 to 5.

6) Computer training has been shown to improve working memory and reasoning, but it is unclear whether such training can improve inhibitory control. Other (non-computer-based) approaches report improvement in inhibitory control as assessed by selective attention (e.g., flanker) or response inhibition (e.g., go/no-go), but none report improvement in the inhibitory control needed to delay gratification.

7) EF training appears to transfer, but the transfer is narrow. Working memory training improves working memory but not inhibition or speed. If the training was only with visual-spatial items, there is little transfer to verbal material. EF gains from martial arts or school curriculum may be wider because the programs themselves address EFs more globally; the transfer may not be wider, but rather the programs address more EF components.

8) Exercise alone may not be as efficacious in improving EFs as exercise plus character development [traditional martial arts (*28*)] or exercise plus mindfulness (*31*).

9) Many different activities can improve EFs, probably including ones not yet studied (such as music training or sports). One key element is a child's willingness to devote time to the activity. Similarly, curricula need to address EFs throughout the day, not only in a module. Repeated practice produces the benefits. Even the best activity for improving EFs done rarely produces little benefit.

10) Computer training has the advantage that it can be done at home. As computer training comes to incorporate more EF components, benefits will likely be seen more widely. These tend to be short-duration interventions, however, as interest in the games wanes and the games' highest levels are reached. Martial arts, yoga, aerobic, or mindfulness activities can be done after school. Because computer training and the other activities just mentioned cost money, they are not possible for all families.

11) Public school curricula hold the greatest promise for accessibility to all and intervening early enough to get children on a positive trajectory from the start and affecting EFs most broadly. Martial arts, yoga, aerobic, or mindfulness activities could be incorporated into school curricula. Although schools are curtailing physical education and the arts, evidence indicates that the opposite is probably needed for the best academic results.

The four curricula-based programs shown to enhance EFs have many commonalities (Table 1). We'd like to highlight two: They do not expect young children to sit still for long. Such expectations are not developmentally appropriate, increase teacher-student tensions, and lead some children to dread school and/or to be wrongly labeled as having ADHD. Second, the programs tend to reduce stress in the classroom; cultivate joy, pride, and self-confidence; and foster social bonding; all of which support efforts to improve EFs and academic achievement.

Stress (*49*), loneliness (*50*), and lack of physical fitness (*17*) impair prefrontal cortex function and EFs. The best approaches to improving EFs and school outcomes will probably be those that (i) engage students' passionate interests, bringing them joy and pride; (ii) address stresses in students' lives, attempting to resolve external causes and to strengthen calmer, healthier responses; (iii) have students vigorously exercise; and (iv) give students a sense of belonging and social acceptance, in addition to giving students opportunities to repeatedly practice EFs at progressively more-advanced levels. The most effective way to improve EFs and academic achievement is probably not to focus narrowly on those alone but to also address children's emotional and social development (as do all four curricula-based programs that improve EFs) and children's physical development (as do aerobics, martial arts, and yoga).

References and Notes

1. A. Miyake *et al.*, *Cognit. Psychol.* **41**, 49 (2000).
2. C. Blair, R. P. Razza, *Child Dev.* **78**, 647 (2007).
3. S. E. Gathercole, S. J. Pickering, C. Knight, Z. Stegmann, *Appl. Cogn. Psychol.* **18**, 1 (2004).
4. M. Prince *et al.*, *Lancet* **370**, 859 (2007).
5. L. Eakin *et al.*, *J. Atten. Disord.* **8**, 1 (2004).
6. J. R. Dunn, *JAMA* **303**, 1199 (2010).
7. C. A. Kusche, E. T. Cook, M. T. Greenberg, *J. Clin. Child Psychol.* **22**, 172 (1993).
8. T. E. Moffitt *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **108**, 2693 (2011).
9. J. Holmes, S. E. Gathercole, D. L. Dunning, *Dev. Sci.* **12**, F9 (2009).
10. T. Klingberg *et al.*, *J. Am. Acad. Child Adolesc. Psychiatry* **44**, 177 (2005).
11. S. Bergman Nutley *et al.*, *Dev. Sci.* **14**, 591 (2011).
12. L. B. Thorell, S. Lindqvist, S. Bergman Nutley, G. Bohlin, T. Klingberg, *Dev. Sci.* **12**, 106 (2009).
13. J. Holmes *et al.*, *Appl. Cogn. Psychol.* **24**, 827 (2010).
14. See tables S1 and S2 for details of each intervention and each outcome measure.
15. M. R. Rueda, M. K. Rothbart, B. D. McCandliss, L. Saccomanno, M. I. Posner, *Proc. Natl. Acad. Sci. U.S.A.* **102**, 14931 (2005).
16. A. P. Mackey, S. S. Hill, S. I. Stone, S. A. Bunge, *Dev. Sci.* **14**, 582 (2011).
17. C. H. Hillman, K. I. Erickson, A. F. Kramer, *Nat. Rev. Neurosci.* **9**, 58 (2008).
18. L. Chaddock, M. B. Pontifex, C. H. Hillman, A. F. Kramer, *J. Int. Neuropsychol. Soc.*; published online 13 April 2011 (10.1017/S1355617711000567).
19. B. W. Tuckman, J. S. Hinkle, *Health Psychol.* **5**, 197 (1986).
20. C. L. Davis *et al.*, *Health Psychol.* **30**, 91 (2011).
21. K. Kamijo *et al.*, *Dev. Sci.*; published online 25 April 2011 (10.1111/j.1467-7687.2011.01054.x).
22. T. A. Uhrich, R. L. Swalm, *Percept. Mot. Skills* **104**, 1035 (2007).
23. H. Budde, C. Voelcker-Rehage, S. Pietrabyk-Kendziorra, P. Ribeiro, G. Tidow, *Neurosci. Lett.* **441**, 219 (2008).
24. F. H. Rauscher *et al.*, *Neurol. Res.* **19**, 2 (1997).
25. S. Bergman-Nutley, thesis, Karolinska Institutet, Stockholm, Sweden (2011).
26. D. M. Castelli, C. H. Hillman, S. M. Buck, H. E. Erwin, *J. Sport Exerc. Psychol.* **29**, 239 (2007).
27. D. P. Coe, J. M. Pivarnik, C. J. Womack, M. J. Reeves, R. M. Malina, *Med. Sci. Sports Exerc.* **38**, 1515 (2006).
28. K. D. Lakes, W. T. Hoyt, *Appl. Dev. Sci.* **25**, 283 (2004).
29. M. E. Trulson, *Hum. Relat.* **39**, 1131 (1986).
30. L. Flook *et al.*, *J. Appl. Sch. Psychol.* **26**, 70 (2010).
31. N. K. Manjunath, S. Telles, *Indian J. Physiol. Pharmacol.* **45**, 351 (2001).
32. See Table 1 for more curricular details.
33. E. Bodrova, D. J. Leong, *Tools of the Mind: The Vygotskian Approach to Early Childhood Education* (Merrill/Prentice Hall, New York, ed. 2, 2007).

34. L. S. Vygotsky, *Mind in Society: The Development of Higher Psychological Processes* (Harvard Univ. Press, Cambridge, MA, 1978).
35. A. Diamond, W. S. Barnett, J. Thomas, S. Munro, *Science* **318**, 1387 (2007).
36. M. Montessori, *Absorbent Mind* (ABC-CLIO, Oxford, 1949).
37. K. Lloyd, *NAMTA J.* **36**, 165 (2011).
38. P. A. Cohen, J. A. Kulik, C. L. C. Kulik, *Am. Educ. Res. J.* **19**, 237 (1982).
39. C. R. Greenwood, J. C. Delquadri, R. V. Hall, *J. Educ. Psychol.* **81**, 371 (1989).
40. M. Mastropieri *et al.*, *Learn. Disabil. Res. Pract.* **16**, 18 (2001).
41. A. Lillard, N. Else-Quest, *Science* **313**, 1893 (2006).
42. C. A. Kusché, M. T. Greenberg, *The PATHS Curriculum* (Developmental Research and Programs, Seattle, WA, 1994).
43. N. R. Riggs, M. T. Greenberg, C. A. Kusché, M. A. Pentz, *Prev. Sci.* **7**, 91 (2006).
44. C. Webster-Stratton, M. J. Reid, *Infants Young Child.* **17**, 96 (2004).
45. C. C. Raver *et al.*, *Early Child. Res. Q.* **23**, 10 (2008).
46. C. C. Raver *et al.*, *Child Dev.* **82**, 362 (2011).
47. C. P. Li-Grining, C. C. Raver, R. A. Pess, paper presented at the Society for Research in Child Development Biennial Meeting, Montreal, Canada, 31 March to 2 April 2011.
48. T. O'Shaughnessy, K. L. Lane, F. M. Gresham, M. Beebe-Frankenberger, *Rem. Spec. Edu.* **24**, 27 (2003).
49. A. F. Arnsten, *Science* **280**, 1711 (1998).
50. J. Cacioppo, W. Patrick, *Loneliness: Human Nature and the Need for Social Connection* (Norton, New York, 2008).

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Supporting Online Material
www.sciencemag.org/cgi/content/full/333/6045/959/DC1
Tables S1 and S2

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REVIEW

Teachers' Language Practices and Academic Outcomes of Preschool Children

David K. Dickinson

Early childhood programs have long been known to be beneficial to children from low-income backgrounds, but recent studies have cast doubt on their ability to substantially increase the rate of children's academic achievement. This Review examines research on the role of language in later reading, describes home and classroom factors that foster early language growth, and reviews research on preschool interventions. It argues that one reason interventions are not having as great an impact as desired is because they fail to substantially change the capacity of teachers to support children's language and associated conceptual knowledge.

Every year, large numbers of children fail to complete high school, and the cost to both the students and society is enormous. It has been estimated that in 2007 in the United States, 16% of youth between ages 16 and 24 were high school dropouts, and that every such student costs roughly $260,000 in lost earnings, taxes, and productivity (*1*). Reading success hinges on acquisition of a cluster of language and print-related competencies in preschool and the early primary grades (*2*). It also is associated with competencies such as mathematical ability and self-regulation (*3*), but here we focus on language.

For many, the seeds of academic failure are sown early and are evident in early reading struggles. Despite sustained efforts by educators, an achievement gap persists between the reading skills of children from more and less advantaged homes (*4*). Language ability at ages three and four predicts later reading comprehension through high school (*5*, *6*), and later language ability builds directly on earlier competencies. Differences in children's language ability and associated capacity emerge early, relate to social demographic factors, and foreshadow future reading success (Fig. 1).

In this article, I review research indicating that a major factor accounting for this reading gap is the language competencies associated with literacy. Between birth and school entrance, there is rapid growth of language and associated competencies essential to later literacy (*3*), and learning gaps associated with these competencies relate to social economic status (SES) (*7*, *8*). Factors in homes and classrooms partially account for differential language growth, and although preschool programs have had some success in meeting children's needs, many have failed to help teachers' language-enhancing practices that are needed to bolster language learning. Without better understanding of the mechanisms by which programs can foster teachers' support for children's language, we may continue to struggle to create programs that reliably result in improved learning.

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The Emergence of Literacy

Although language is a universal human capability, the rate of acquisition of vocabulary (*8*) and syntax (*9*) varies and is associated with SES. By age three, there are substantial economic-related differences in receptive vocabulary that persist to age 13 (*7*) for all groups except African-American children, for whom this gap continues to grow until school entry at age five. For example, the average child enrolling in Head Start is roughly one year below national norms in receptive vocabulary.

Researchers are making progress in identifying how early home experiences account for early differences in the rate at which children learn new vocabulary and how these experiences are influenced by SES and parenting. Parents gesture when communicating even before their infants begin to talk, and the number of different gestures mothers use with their 14-month-old children is associated with the size of children's vocabulary at age 54 months. Mothers from higher SES backgrounds gesture more frequently (*10*). Similarly, the amount of language that children hear in their first months, from their parents, affects their ability to quickly understand words at 18 months (*11*), and this speed of lexical access predicts vocabulary size in preschool (*12*) and as late as age eight (*13*). Additionally, the amount of verbal communication by mothers when they interact with 30-month-old children also predicts the size of children's vocabularies a year later (*8*). In this study, when mothers' beliefs and knowledge about child development were taken into account, SES no longer predicted children's later verbal ability, indicating that parents from all backgrounds may be able to provide appropriate language support to young children but may not recognize the value of parenting strategies that support language learning. Language researchers also have identified a number of other features of interactions that support language learning through the preschool years, such as the variety of words used and mother's ability to be responsive to children's efforts to talk and to extend and clarify what they say (*14*).

The pace of language growth before school entry also predicts other capacities that undergird later academic success. The emergence of self-regulation ability is a capacity linked to later academic achievement (*3*). Phonological awareness development, the ability to reflect on the sounds of language, is critical to decoding and also is associated with language development in the preschool period (*15*, *16*). Age four language also predicts the ability to sound out words in kindergarten (*17*) and first grade (*6*).

Although the speed of language acquisition is strongly affected by experience, genetic studies indicate that roughly a third of the variability in language and later reading is determined by genetic factors (*18*, *19*), leaving substantial opportunities for early interventions to have positive impacts. Given that early environmental factors shape language, children at high risk of educational problems should begin to receive

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Supporting Online Material for

Interventions Shown to Aid Executive Function Development in Children 4 to 12 Years Old

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This PDF file includes:

Supplementary Online Materials

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i. Table S1: Details about Participants and Interventions shown to aid Executive Function Development in Children 4-12 years old

Ref #	Author/ Year	Number of Subjects		Subject Characteristics			Intervention			Active Control Group?	Dosage, Frequency & Duration			
		Ttl	Per Group	Age (yrs)	Sex	Other	Kind	Incremental increases in difficulty?	What EF skills were targeted?		Session Duration (in minutes)	# of Sessions per Week	Total Time Period (in weeks)	Total # of Hours
Computerized Training: Cogmed Training System (*S1*)														
10	Holmes et al. (2009)	42	1) Working memory (WM) = 22 2) Active control (non-incrementing version of training games) = 20	8-11	M & F	All had poor initial working memory (low working memory span).	Working memory training: Cogmed computerized training system	Yes	- verbal WM - visuospatial WM	Yes	30-45	~2-5	5-8	15-17 (*S2*)
11	Klingberg et al. (2005)	53	1) Working memory (WM) = 27 2) Active control (non-incrementing version of training games) = 26	7-12	M & F	All were diagnosed with ADHD & non-medicated.	Working memory training: Cogmed computerized training system	Yes	- verbal WM - visuospatial WM	Yes	40	~4-5	5-6	17
12	Bergman-Nutley et al. (2011)	101	1) Working memory (WM) = 24 2) Non-verbal reasoning (NVR) = 25 3) Combined (CB) = 27 4) Placebo (PL) (non-incrementing version of training games) = 25	4	M & F	All families needed to have access to a PC computer & internet (parents supervised the training at home).	1) Working memory training: Cogmed computerized training system 2) Non-verbal reasoning training: 3 Leiter battery tests (RP,SO,CL [*S4*]) 3) Combined training: combination of NVR and WM training 4) Placebo training: combined, lowest level of difficulty	Yes	1) WM training - verbal WM - visuospatial WM 2) NVR training - identifying patterns - deducing rules - matching by ≥1 dimensions & ignoring others	Yes	15	5	5-7	~6
13	Thorell et al. (2009)	65	1) Working memory (WM) = 17 2) Inhibition training = 18 3) Active control (computer games [*S5*]) = 14 4) Passive control (no treatment) =16	4-5	M & F	None	1) Working memory training: Cogmed computerized training system 2) Inhibition training - Go/No-go task - Flanker task - Stop Signal task	Yes	1) WM training - tasks focused on visuospatial WM 2) Inhibition training - inhibition of a prepotent motor response - interference control - stopping of an ongoing response	Yes	15	~4-5	5	6
14	Holmes et al. (2010)	25	1) Working memory (WM) = 25 T1: Off medication T2: Pre-training, on medication T3: Post-training, on medication T4: 6 months later, on medication	8-11	M & F	All were diagnosed with ADHD & taking stimulant medication.	Working memory training: CogMed computerized training system	Yes	- verbal WM - visuospatial WM	No	30-45	~2-5	5-8	15-17 (*S6*)

Ref #	Author/ Year	Number of Subjects		Subject Characteristics			Intervention			Active Control Group?	Dosage, Frequency & Duration			
		Ttl	Per Group	Age (yrs)	Sex	Other	Kind	Incremental increases in difficulty?	What EF skills were targeted?		Session Duration (in minutes)	# of Sessions per Week	Total Time Period (in weeks)	Total # of Hours
Computerized Training: Other														
15	Rueda et al. (2005)	73	4-year-olds 1) Attention training = 24 2) Inactive control (watch videos) = 13 3) No treatment control = 12 6-year-olds 1) Attention training = 12 2) Inactive control (watch videos) = 12	4 & 6	M & F	All were middle-income.	Computerized attention training included: - conflict resolution sets - inhibitory control exercises (4-year-olds on a Stroop-like task, 6-year-olds on a Go/No-go task)	Yes	- attention - memory - inhibitory control	No (*S7*)	40	~2-3	2-3	~3
Hybrids of Computer and Non-computer Games														
16	Mackey et al. (2010)	28	1) Reasoning training = 17 2) Speed training = 11	7-9	M & F	All attended a school with a history of low statewide test scores and a high % of low-income students.	1) Reasoning training (fluid reasoning) 2) Speed training (processing speed) *combination of 10-12 commercially-available computerized & non-computerized games (*S8*)	Yes	1) Reasoning training - joint consideration of several task rules, relations, or steps 2) Speed training - rapid visual detection - rapid motor response	Yes	60	2	8	16
Aerobic Exercise and Sports														
19	Tuckman & Hinkle (1986)	154	1) Aerobic running = 77 2) Regular Phys. Ed. = 77	8-12	M & F	All attended a university-affiliated "research" school.	Aerobic running	Yes	None	Yes	30	3	12	18
20	Davis et al. (2011)	171	1) High-dose aerobic exercise = 60 2) Low-dose aerobic exercise = 55 3) No program control = 56	7-11	M & F	All were sedentary & overweight or obese (85th percentile body mass index).	Aerobic exercise: - included running games, jump rope, modified basketball and soccer - high-dose was 40 minutes / day - low-dose was 20 minutes / day	Yes	None	No	20 or 40	5	~13	~22 or 43
21	Kamijo et al. (2011)	43	1) Physical activity program = 22 2) No program control = 21	7-9	M & F	None	Physical activity: - aerobic exercises - muscle fitness	Yes	None	No	120	5	36	300

Ref #	Author/ Year	Number of Subjects		Subject Characteristics			Intervention			Active Control Group?	Dosage, Frequency & Duration			
		Ttl	Per Group	Age (yrs)	Sex	Other	Kind	Incremental increases in difficulty?	What EF skills were targeted?		Session Duration (in minutes)	# of Sessions per Week	Total Time Period (in weeks)	Total # of Hours
Martial Arts and Mindfulness Practices														
28	Lakes & Hoyt (2004)	207	1) LEAD Program Tae-Kwon-Do Martial Arts training (*S12*) = 105 2) Regular Phys. Ed. classes = 102 *Randomly assigned by homeroom class	5-11	M & F	All attended a private school and most were high-middle or high-income.	Tae-Kwon-Do Martial Arts training: - used traditional Moo Gong Ryu techniques in environment of respect, discipline and self-control - ask self 3 questions: 1. Where am I? 2. What am I doing? 3. What should I be doing?	Yes	- self-control (inhibition) - discipline - sustained concentration - self-monitoring - planning	Yes	45	~2-3	16	~28
30	Flook et al. (2010)	64	1) Mindfulness Awareness Practices (MAPS) = 32 2) Control (silent reading) = 32	7-9	M & F	None	MAPS: - sitting meditation - games to promote sensory awareness, attention regulation, awareness of others and environment - body scans	Yes	- top-down control of attention - monitoring attention	Yes	30	2	8	8
31	Manjunath & Telles (2001)	20	1) Yoga = 10 2) Active control (physical training) = 10	10-13	F only	None	Yoga program: - physical training - relaxation - awareness training	Yes	- top-down control of attention	Yes	75	7	4	~35
Classroom Curricula														
35	Diamond et al. (2007)	147	1) Tools of the Mind = 85 2) School district curriculum = 62	4-5	M & F	All were low-income & most were Hispanic. Groups were closely matched on demographics.	Tools of the Mind curriculum: - see text & Table 1	Yes	- inhibitory control of behavior & attention - sustained attention - working memory - switching - planning	Yes	Entire school day	5	Entire school year	860
41	Lillard & Else-Quest (2006)	112	5-year-olds 1) Montessori = 30 2) Other school curricula = 25 12-year-olds 1) Montessori = 29 2) Other school curricula = 28 *subjects were not randomly assigned	5 & 12	M & F	All were low-income & had entered lottery for Montessori school. Selection from lottery was random.	Montessori curriculum: - see text & Table 1	Yes	- inhibitory control of behavior & attention - sustained attention - working memory - planning	Yes	Entire school day	5	See footnote section for details (*S15*)	

Ref #	Author/ Year	Number of Subjects		Subject Characteristics			Intervention			Active Control Group?	Dosage, Frequency & Duration			
		Ttl	Per Group	Age (yrs)	Sex	Other	Kind	Incremental increases in difficulty?	What EF skills were targeted?		Session Duration (in minutes)	# of Sessions per Week	Total Time Period (in weeks)	Total # of Hours
Add-ons to Classroom Curriculum														
43	Riggs et al. (2006)	318	1) PATHS (Promoting Alternative Thinking Strategies) added to school district curriculum = 153 2) School district curriculum = 165	7-9	M & F	All were low or middle-income.	PATHS curriculum: - see text & Table 1	Yes	- inhibitory control (self-control) including waiting before acting - emotion regulation - problem-solving - planning	Yes	20-30	3	24	~30
45 46	Raver et al. (2008, 2011)	467	1) Chicago School Readiness Project (CSRP) added to Head Start = 238 2) Head Start = 229	3-4	M & F	All were low-income, considered at-risk & came from high-poverty neighborhoods.	CSRP: - see text & Table 1	Yes	None	Yes	Entire school day	5	Entire school year	

ii. Table S2: Executive Function Outcomes: Including Assessment Measures Used and Effect Sizes

Ref #	Author/ Year	Executive Function Outcomes						
		Positive EF Transfers	**Size of Effect**	**Positive transfers were narrow**	**Those with worse EFs benefit most**	**Larger group differences for more EF-demanding conditions**	**Progressively increasing challenge during training is important for benefits**	**No Transfer on EF Measures**
Computerized Training: Cogmed Training System (*S1*)								
10	Holmes et al. (2009)	1) WM training group showed transfers to (*S2*): - subtests from the AWMA: • **verbal WM** (Counting Recall) . . . . • **verbal STM** (Word Recall, Digit Recall) . . . . • **visuospatial WM** (Mr. X, Spatial Recall) . . . . • **visuospatial STM** (Dot Matrix, Block Recall) . . . . - **verbal WM task** (Following Instructions task) . . . . 2) Active control group showed transfers to (*S2*): - subtests from the AWMA: • **verbal WM** (Counting Recall) . . . . • **verbal STM** (Word Recall, Digit Recall) . . . . *Based on pre- to post- training comparison	 Large Medium Large Large Large Medium Medium	Yes	All started low.	n/a	Yes	1) None; WM training group only showed positive transfers. 2) Active control group showed no transfer to(*S2*): - subtests from the AWMA: • **visuospatial WM** (Mr. X, Spatial Recall) • **visuospatial STM** (Dot Matrix, Block Recall) - **verbal WM task** (Following Instructions task)
11	Klingberg et al. (2005)	1) WM training group showed transfers to (*S3*): - **verbal WM** (Digit Span – WISC-III) . . . . - **visuospatial WM** (Span Board – WAIS-RNI) . . . . - **inhibition** (Stroop task) . . . . - **non-verbal reasoning** (Raven's Matrices) . . . . - parent-reported Conners Rating Scale: • **inattention decreased**. . . . . • **hyperactivity/impulsivity decreased** . . . . *Based on control group comparison	 Medium Large Medium Medium Large Medium	Yes	All had ADHD.	n/a	Yes	1) WM training group showed no transfer to: - teacher-reported Conners Rating Scale: • **inattention** • **hyperactivity/impulsivity**
12	Bergman-Nutley et al. (2011)	1) WM training group showed transfer to (*S4*): - **non-verbal memory / reasoning** (Odd One Out - AWMA) 2) NVR training group showed transfers to (*S4*): - **non-verbal analogical reasoning & problem solving** (Raven's Matrices B, Block Design - WPPSI) . . . . - **non-verbal memory / reasoning** (Odd One Out - AWMA) 3) CB training group showed transfers to (*S4*): - **non-verbal memory / reasoning** (Odd One Out - AWMA) *Odd One Out had a reasoning component and reasoning training tended to aid its performance *Based on control group (PL) comparison	 Large Large Small (trend only) Small	Yes	n/a	n/a	Yes	1) WM training group showed no transfer to(*S4*): - **problem solving** (Leiter tests, Raven's Matrices, Block Design - WPPSI) - **verbal WM** (Word Span) 2) NVR training group showed no transfer to(*S4*): - **problem solving** (non-verbal Gestalt completion on Raven's Matrices A & AB) - **verbal WM** (Word Span) 3) CB training group showed no transfer to(*S4*): - **problem solving** (Raven's Matrices, Block Design - WPPSI) - **verbal WM** (Word Span)
13	Thorell et al. (2009)	1) WM training group showed transfers to (*S5*): - **visuospatial WM** (Span Board – WAIS-RNI) . . . . - **verbal WM** (Word Span) . . . . - **auditory attention** (Auditory Continuous Performance task - NEPSY) . . . . *Based on comparison with the 2 control groups combined	 Large Large Medium	Yes	n/a	n/a	n/a	1) WM training group showed no transfer to(*S5*): - **response inhibition** (Go/No-go) - **inhibition & WM** (Day-Night Stroop task) - **problem solving** (Block Design – WPPSI-R) - **inhibitory control** (Go/No-go) - **sustained attention** (Go/No-go) 2) Inhibition training group showed no transfer.
14	Holmes et al. (2010)	1) From T1 to T2, WM training group showed transfers to(*S6*): - subtests from the AWMA: • **visuospatial WM** (Mr. X, Spatial Span) . . . . 2) From T2 to T3, WM training group showed transfers to(*S6*): - subtests from the AWMA: • **verbal WM** (Backward Digit Recall, Listening Recall) • **verbal STM** (Digit Recall) . . . . • **visuospatial WM** (Mr. X, Odd One Out) . . . . • **visuospatial STM** (Dot Matrix, Mazes Memory) . . . . . *Based on comparisons across time	 Medium Medium Medium Small Large	Yes	All had ADHD.	n/a	n/a	1) From T1 to T2, WM training group showed no transfer to (*S6*): - subtests from the AWMA: • **verbal WM** (Backward Digit Recall, Counting Recall) • **verbal STM** (Digit Recall, Word Recall) • **visuospatial STM** (Dot Matrix)

Ref #	Author/ Year	Executive Function Outcomes						
		Positive EF Transfers	**Size of Effect**	**Positive transfers were narrow**	**Those with worse EFs benefit most**	**Larger group differences for more EF-demanding conditions**	**Progressively increasing challenge during training is important for benefits**	**No Transfer on EF Measures**
Computerized Training: Other								
15	Rueda et al. (2005)	4-year-olds: Attention training showed transfers to (*S7*): **- abstract reasoning** (Matrices – K-BIT) . . . . 6-year-olds: Attention training showed no transfers but showed more efficient adult-like ERPs during attention task. *Based on control group comparison	?	Yes	All were middle-income.	n/a	n/a	4-year-olds showed no transfer to (*S7*): - **selective attention** (Flanker task) - **parent-reported temperament** (CBQ) 6 year-olds showed no transfer to (*S7*): - **selective attention** (Flanker task) - **parent-reported effortful control** (CBQ)
Hybrids of Computer and Non-computer Games								
16	Mackey et al. (2010)	1) Reasoning training showed transfers to (*S8*): - **fluid reasoning** (Matrix task – TONI-3) . . . . - **processing speed** (Cross-Out – WJ-R) . . . . - **working memory** (Spatial Span - WMS) . . . . 2) Speed training showed transfers to (*S8*): - **processing speed** (Coding B – WISC-IV, Cross-Out - WJ-R) . . . . *Based on baseline score comparison	Large Medium Medium Large	Yes	All were low-income.	n/a	n/a	1) Reasoning training showed no transfer to (*S8*): - **processing speed** (Coding B – WISC-IV) - **working memory** (Digit Span - WMS) 2) Speed training showed no transfer to (*S8*): - **fluid reasoning** (Matrix task – TONI-3) - **working memory** (Digit Span - WMS, Spatial Span - WMS)
Aerobic Exercise and Sports								
19	Tuckman & Hinkle (1986)	Aerobic running benefitted: - **creativity & cognitive flexibility** (Alternate Uses test) . . . - girls reported to show more creative involvement in class *Based on control group comparison	Large	n/a	n/a	n/a	n/a	None; only benefits reported.
20	Davis et al. (2011)	High-dosage Aerobics benefitted (*S10*): - **strategy generation & application, self-regulation, intentionality, utilization of knowledge** (CAS Planning scale) . . . . *Dose-response effect demonstrated *Based on control group comparison	Small	n/a	All were sedentary & over-weight.	n/a	n/a	Aerobics did not benefit (*S10*): - **focused attention, resistance to distraction** (CAS Attention scale) - **spatial/logical reasoning** (CAS Simultaneous scale) - **analysis/recall of stimuli arranged in sequence** (CAS Successive scale)
21	Kamijo et al. (2011) (*S11*)	Aerobics benefitted (*S11*): - **working memory** (modified Sternberg task) . . . . *Based on control group comparison	Small	n/a	n/a	n/a	n/a	None; only benefits reported.

Ref #	Author/ Year	Executive Function Outcomes						
		Positive EF Transfers	**Size of Effect**	**Positive transfers were narrow**	**Those with worse EFs benefit most**	**Larger group differences for more EF-demanding conditions**	**Progressively increasing challenge during training is important for benefits**	**No Transfer on EF Measures**
Martial Arts and Mindfulness Practices								
28	Lakes & Hoyt (2004)	Tae-Kwon-Do Martial Arts benefitted (*S12*): - subtests from the Response to Challenge Scale: • **cognitive self-regulation (focused attention)** . . . . . • **affective self-regulation (not quitting)** . . . . *Effect greater for boys than girls *Effect greater for older kids (grades 4 and 5) and smaller for younger kids (grade 1) *Based on control group comparison	 Medium Medium	n/a	All were middle-high or high income. Yes; Boys benefitted more than girls.	n/a	n/a	None; only benefits reported.
30	Flook et al. (2010)	Mindfulness benefitted (*S13*): - parent ratings on the BRIEF: • **shifting (cognitive flexibility)** . . . . • **emotion regulation** . . . . • **WM** . . . . • **monitoring**. . . . . -teacher ratings on the BRIEF: • **shifting (cognitive flexibility)** . . . . • **planning / organizing** . . . . • **monitoring** . . . . *Teachers were not blind to group assignment *Based on change x group comparison (change over time in intervention group was greater than change over time in control group)	 Large Large Medium Large Medium Medium Medium	n/a	Yes	n/a	n/a	Mindfulness did not benefit (*S13*): - parent ratings on the BRIEF: • **inhibition** • **planning** / **organizing** • **organization of materials** - teacher ratings on the BRIEF: • **inhibition** • **emotion regulation** • **WM** • **organization of materials**
31	Manjunath & Telles (2001)	Yoga benefitted (*S14*): - **planning** (Tower of London) . . . . • faster & in fewer moves *Based on pre- to post-training comparison	 ?	n/a	n/a	Yes	n/a	None; only benefits reported.
Classroom Curricula								
35	Diamond et al. (2007)	Tools of the Mind benefitted: - **inhibition** (Hearts and Flowers-Incongruent) . . . . - **switching** / **WM** / **inhibition** (Hearts and Flowers-Mixed) - **selective attention** (Flanker) . . . . - **selective attention/switching** (Reverse Flanker) . . . . *Based on control group comparison	 Small Large Small Large	No	All were low-income & at-risk.	Yes	n/a	None; only benefits reported.
41	Lillard & Else-Quest (2006)	Montessori benefits: 1) 5-year-olds - **switching / WM / inhibition** (Card Sort task) . . . . 2) 12-year-olds - **creativity** (Story Completion task) . . . . *Based on control group comparison	 Medium Large	n/a	All were low-income.	n/a	n/a	Montessori did not benefit: - **delay of gratification assessed at age 5**

Ref #	Author/ Year	Executive Function Outcomes						
		Positive EF Transfers	**Size of Effect**	**Positive transfers were narrow**	**Those with worse EFs benefit most**	**Larger group differences for more EF-demanding conditions**	**Progressively increasing challenge during training is important for benefits**	**No Transfer on EF Measures**
Add-ons to Classroom Curriculum								
43	Riggs et al. (2006)	PATHS benefitted: - **inhibiton & WM** (Stroop task) . . . . - **cognitive flexibility** (Verbal Fluency) . . . . *Based on control group comparison	Small Small	No	All were low or middle-income.	n/a	n/a	None; only benefits reported.
45 46	Raver et al. (2008, 2011)	CSRP benefitted (*S17*): - **concentration** (Balance Beam - PSRA) . . . . - **inhibition & WM** (Pencil Tap - PSRA) . . . . - **attention** & i**mpulsivity** (Global Assessor report - PSRA)	Medium Medium Medium	n/a	All were low-income, at-risk & came from high-poverty areas.	n/a	n/a	CSRP did not benefit (*S17*): - **delay of gratification** (PSRA)

iii. Table S3: Other Cognitive & Non-Cognitive Outcomes and Long-term Assessments

Ref #	Author/ Year	Other: Both Cognitive & Non-Cognitive			Results of Assessments ≥ 6 Months Later
		Other Cognitive & Non-Cognitive Skills Improved	**Size of Effect**	**Other Cognitive & Non-Cognitive Skills Not Affected**	
Computerized Training: Cogmed Training System (*S1*)					
10	Holmes et al. (2009)	1) WM training group showed no transfer to other cognitive or non-cognitive skills.	n/a	1) WM training group showed no transfer to (*S2*): - **verbal IQ** (WASI) - **performance IQ** (WASI) - **basic word reading** (WORD) - **mathematical reasoning** (WOND)	Assessed 6 months later: 1) WM training group showed lasting improvements on (*S2*): - subtests from the AWMA: • **verbal WM** (Counting Recall) • **visuospatial WM** (Mr. X, Spatial Recall) • **visuospatial STM** (Dot Matrix, Block Recall) - **verbal WM task** (Following Instructions task) - **mathematical reasoning** (WOND)
11	Klingberg et al. (2005)	None tested	n/a	None tested	Not tested
12	Bergman-Nutley et al. (2011)	None tested	n/a	None tested	Not tested
13	Thorell et al. (2009)	None tested	n/a	None tested	Not tested
14	Holmes et al. (2010)	1) WM training group showed no transfer to other cognitive or non-cognitive skills.	n/a	1) From T1 to T2, WM training group showed no transfer to (*S6*): - **verbal IQ** (WASI) - **performance IQ** (WASI) 2) From T2 to T3, WM training group showed no transfer to (*S6*): - **verbal IQ** (WASI) - **performance IQ** (WASI)	Assessed 6 months later: From T2 to T4, WM training group showed lasting improvements on (*S6*): - subtests from the AWMA: • **verbal WM** (Backward Digit Recall) • **visuospatial WM** (Mr. X) • **visuospatial STM** (Dot Matrix)

Ref #	Author/ Year	Other: Both Cognitive & Non-Cognitive			Results of Assessments ≥ 6 Months Later
		Other Cognitive & Non-Cognitive Skills Improved	**Size of Effect**	**Other Cognitive & Non-Cognitive Skills Not Affected**	
Computerized Training: Other					
15	Rueda et al. (2005)	4-year-olds: Attention training showed transfers to (*S7*): - **IQ composite score** (K-BIT) . . . . 6-year-olds: Attention training showed transfers to (*S7*): - **verbal IQ** (K-BIT vocabulary)	? ?	None; only benefits reported.	Not tested
Hybrids of Computer and Non-computer Games					
16	Mackey et al. (2010)	None tested	n/a	None tested	Not tested
Aerobic Exercise and Sports					
19	Tuckman & Hinkle (1986)	Aerobic running showed no benefits to other cognitive or non-cognitive skills.	n/a	Aerobic running did not benefit (*S9*): - **classroom behavior** (Devereaux behavior scale) - **self-concept** (Piers-Harris scale) - **perceptual-motor ability** (Bender-Gestalt test) - **planning ability & visual-motor coordination** (Maze Tracing Speed test)	Not tested
20	Davis et al. (2011)	Aerobics benefitted (*S10*): - **mathematics achievement** (WJ-III)	Small	Aerobics did not benefit (*S10*): - **reading achievement** (WJ-III)	Not tested
21	Kamijo et al. (2011)	None tested	n/a	None tested	Not tested

Ref #	Author/ Year	Other: Both Cognitive & Non-Cognitive			Results of Assessments ≥ 6 Months Later
		Other Cognitive & Non-Cognitive Skills Improved	**Size of Effect**	**Other Cognitive & Non-Cognitive Skills Not Affected**	
Martial Arts and Mindfulness Practices					
28	Lakes & Hoyt (2004)	Tae-Kwon-Do Martial Arts benefitted (*S12*): - **prosocial behavior** (SDQT) . . . . - **mathematics** (WISC-III) . . . . - **conduct** (SDQT) . . . . *Improvement in conduct significant for boys only	Small Small Medium	Tae-Kwon-Do Martial Arts did not benefit (*S12*): - **emotional symptoms** (SDQT) - **hyperactivity** (SDQT) - **peer problems** (SDQT) - **digit span** (WISC-III) - **self-esteem** (Self-Esteem Inventory)	Not tested
30	Flook et al. (2010)	Mindfulness benefitted (*S13*): - parent ratings on the BRIEF: • **initiate** . . . . -teacher ratings on the BRIEF: • **initiate**	Large Medium	None tested	Not tested
31	Manjunath & Telles (2001)	None tested	n/a	None tested	Not tested
Classroom Curricula					
35	Diamond et al. (2007)	None tested	n/a	None tested	Not tested
41	Lillard & Else-Quest (2006)	Montessori benefits (*S15*): 1) 5-year-olds - **letter-word ID** (WJ-III) . . . . - **phonological decoding ability** (WJ-III) . . . . - **math skills** (WJ-III) . . . . - **higher level of reasoning referring to justice/ fairness** (Social problem-solving) . . . . **- more positive shared play** (playground observation) **- less ambiguous rough play** (playground observation) 2) 12-year-olds - **sophisticated sentence structure** (Narrative Composition) . . . . **- positive social strategies** (Social problem-solving) . . . - **sense of school as community** (questionnaire)	Medium Medium Medium Large Medium Large Medium Large Medium	Montessori did not benefit (*S15*): 1) 5-year-olds - **vocabulary** (WJ-III) **- spatial reasoning** (WJ-III) - **concept formation** (WJ-III) 2) 12-year-olds - **any cognitive** / **academic measures** (WJ-III)	Not tested

Ref #	Author/ Year	Other: Both Cognitive & Non-Cognitive			Results of Assessments ≥ 6 Months Later
		Other Cognitive & Non-Cognitive Skills Improved	Size of Effect	Other Cognitive & Non-Cognitive Skills Not Affected	
Add-ons to Classroom Curriculum					
43	Riggs et al. (2006)	None tested	n/a	None tested	- **EFs predicted fewer internalizing or externalizing behavior problems 1 year later** (CBCL) (*S16*)
45 46	Raver et al. (2008, 2011)	CSRP benefitted (*S17*): - **vocabulary** (PPVT) . . . . - **letter**-**naming** (Letter-Naming task) . . . . - **mathematics skills** (Early Math Skills)	 Small Small Small	None; only benefits reported.	- **EFs predicted academic achievement up to 3 years later on math and reading**

iv. Supplementary Online References and Notes

S1. Cogmed Training has two different working memory training programs for children
a) CogMed JM for preschoolers used by Thorell et al. (2009) & Bergman Nutley et al. (2011)
b) CogMed RM for school-age children used by Klingberg et al. (2005) & Holmes et al. (2009, 2010)

S2. Holmes et al. (2009)
Dosage & Duration: Difficult to be specific about dosage and duration because an adaptive paradigm was used which necessarily differs for each child depending on ability level.
AWMA - Automated Working Memory Assessment [T.P. Alloway, *Automated working memory assessment* (Harcourt, Oxford, 2007).]
Following Instructions task - a practical assessment of working memory use in the classroom [S.E. Gathercole *et al. Applied Cog. Psychol.* **22,** 1019 (2008).]
WASI - Wechsler Abbreviated Scales of Intelligence [D. Wechsler, *Wechsler abbreviated scale of intelligence* (Harcourt, London, 1999).]
WORD - Wechsler Objective Reading Dimensions [D. Wechsler, *Wechsler objective reading dimensions (WORD)* (Psychological Corporation, New York, 1993).]
WOND - Wechsler Objective Number Dimensions [D. Wechsler, *Wechsler objective number dimensions (WOND)* (Psychological Corporation, New York, 1996).]

S3. Klingberg et al. (2005)
WISC-III - Wechsler Intelligence Scales for Children – III [D. Wechsler, *WISC-III: Wechsler intelligence scale for children* (Psychological Corporation, San Antonio, 1991).]
WAIS-RNI - Wechsler Adult Intelligence Scale – Revised [D. Wechsler, *WAIS-R manual* (Psychological Corporation, New York, 1981).]

S4. Bergman-Nutley et al. (2011)
Intervention: Non-verbal reasoning training involved 3 Leiter battery tests: 1) RP - Repeated Patterns, 2) SO - Sequential Orders, 3) CL - Classifications
Leiter Battery: [G.H. Roid, L.J. Miller, *Leiter international performance scale-revised: Examiner's manual* (Stoelting Co., Wood Dale, 1997).]
AWMA - Automated Working Memory Assessment [T.P. Alloway, *Automated working memory assessment* (Harcourt, Oxford, 2007).]
Raven's Colored Progressive Matrices: Sets A, B, & AB [J.C. Raven, *Manual for Raven's progressive matrices* (Oxford Psychologists Press, Oxford, 1998).]
WPPSI - Wechsler Preschool and Primary Scale of Intelligence
[D. Wechsler, *Wechsler preschool and primary scale of intelligence – third edition (WPPSI-III)* (Psychological Corporation, New York, 2004).]

S5. Thorell et al. (2009)
Subject Groups: Active control group played computerized games with little demand on WM & inhibition.
WAIS-RNI - Wechsler Adult Intelligence Scale – Revised [D. Wechsler, *WAIS-R manual* (Psychological Corporation, New York, 1981).]
NEPSY - Developmental Neuropsychological Assessment
[M. Korkman, S.L. Kemp, U. Kirk, *NEPSY – A developmental neuropsychological assessment (*Psychological Corporation, San Antonio, 1998).]
WPPSI-R - Wechsler Preschool and Primary Scale of Intelligence – Revised
[D. Wechsler, *WPPSI-R. Wechsler preschool and primary scale of intelligence – revised* (Psychological Corporation, New York, 1995).]

S6. Holmes et al. (2010)
Dosage & Duration: Difficult to be specific about dosage and duration because an adaptive paradigm was used which necessarily differs for each child depending on ability level.
AWMA - Automated Working Memory Assessment [T.P. Alloway, *Automated working memory assessment* (Harcourt, Oxford, 2007).]
WASI - Wechsler Abbreviated Scale of Intelligence [D. Wechsler, *Wechsler abbreviated scale of intelligence* (Harcourt, London, 1999).]

S7. Rueda et al. (2005)
Control Group: Authors consider this an active control condition and note that subjects had to periodically answer questions about the videos they were watching.
K-BIT – Kaufman Brief Intelligence Test [A.S. Kaufman, N.L. Kaufman, *Kaufman brief intelligence test – manual* (American Guidance Service, Circle Pines, 1990).]
CBQ – Children's Behavior Questionnaire [M.K. Rothbart, S.A. Ahadi, K. Hershey, *Merrill Palmer Quart.* **40**, 21 (1994).]

S8. Mackey et al. (2010)
Training Games: List of computerized and non-computerized games
1) Reasoning games: Computerized (Azada, Azada II), Nintendo DS (Big Brain Academy, Picross, Professor Brainium's Games, Neves, Pipe Mania), Non-computerized (Set, Qwirkle, Rush Hour, Tangoes, Chocolate Fix)
2) Processing speed games: Computerized (Feeding Frenzy, Super Cow, Bricks of Atlantis), Nintendo DS (Nervous Brickdown, Super Monkey Ball, Mario Kart, Ratatouille), Non-computerized (Spoons, Pictureka, Speed, Blink, Perfection)
TONI-3 - Test of Non-verbal Intelligence [L. Brown, R.J. Sherbenou, S.K. Johnsen, *Test of nonverbal intelligence examiner's manual* (Pro. Ed., Austin, ed. 3, 1997).]
WJ-R - Woodcock-Johnson Revised [R.W. Woodcock, M.B. Johnson, *Woodcock-Johnson psycho-educational battery- revised* (Riverside, Chicago, 1989).]
WMS - Wechsler Memory Scale [D. Wechsler, *Wechsler memory scale- revised manual* (Psychological Corporation, San Antonio, 1987).]
WISC-IV - Wechsler Intelligence Scale for Children – IV [D. Wechsler, *Wechsler intelligence scale for children – fourth edition* (Psychological Corporation, San Antonio, 2003).]

S9. Tuckman & Hinkle (1986)
Devereaux Elementary School Behavior Rating Scale [M. Swift, *Devereaux elementary school behavior rating scale II manual* (Devereaux Foundation, Devon, 1982).]
Piers-Harris Children's Self-Concept Scale [E.V. Piers, D.B. Harris, *J. Educ. Psychol.* **55**, 91 (1964).]

S10. Davis et al. (2011)
CAS - Cognitive Assessment System [J.A. Naglieri, *The essentials of CAS assessment* (Wiley, New York, 1999).]
1) Planning scale - strategy generation & application, self-regulation, intentionality, utilization of knowledge
Matching numbers: find and underline the 2 matching numbers in each of the 8 rows of numbers; strategy use leads to better results
Planned codes: associate letters to test items, complete a page using codes (e.g. XX or OX) corresponding to letters (e.g. A, B, C) where the organization of codes varies so one must update; strategy use leads to better results
Planned connections: draw lines to connect numbers and letters in alternating sequence
2) Attention scale - focused, selective cognitive activity, resistance to distraction
Modified Stroop test
Number detection: identify single digit numbers only when they appear in a specific font)
Receptive attention: perform letter discrimination on the basis of physical identity (r,r) or conceptual (r, R)
WJ-III - Woodcock-Johnson Tests of Achievement III [R.W. Woodcock, K.S. McGrew, N. Mather, *Woodcock-Johnson III* (Riverside Publishing, Rolling Meadows, 2001).]

S11. Kamijo et al. (2011)
Modified Sternberg task - EEG (electroencephalogram) recording taken while performing task [S. Sternberg, *Science* **153**, 652 (1966).]

S12. Lakes & Hoyt (2004)
Intervention: LEAD - Leadership Education through Athletic Development
Response to Challenge Scale [K.D. Lakes, W.T. Hoyt, *The response to challenge scale (RCS)* (Orange County, 2003).]
Physical self-regulation - physical control and skillfulness from awkward to skillful
Cognitive self-regulation - ability to focus attention and efforts on task at hand from distractible to focused
Affective self-regulation - assess self-confidence, emotional control, persistence and will from quitting to persevering
SDQT - Strengths and Difficulties Questionnaire [R. Goodman, *J. Child Psychol. Psyc.* **38**, 581 (1997).]
WISC-III - Wechsler Intelligence Scale for Children - III [D. Wechsler, *WISC-III: Wechsler intelligence scale for children* (Psychological Corporation, San Antonio, 1991).]

S13. Flook et al. (2010)
Teacher & Parent BRIEF - Behavior Rating Inventory of Executive Function
[G.A. Gioia, P.K. Isquith, S.C. Guy, L. Kenworthy, *Behavior rating inventory of executive function* (Psychological Assessment Resources, Lutz, 2000).]

S14. Manjunath & Telles (2001)
Tower of London – Yoga group showed decreased planning time, decreased execution time & decreased number of moves.

S15. Lillard & Else-Quest (2006)
Dosage & Duration: Duration information difficult to specify as subjects in the study were 5- and 12-year-old students already enrolled in the Montessori curriculum.
WJ-III - Woodcock-Johnson - III [R.W. Woodcock, K.S. McGrew, N. Mather, *Woodcock-Johnson III* (Riverside Publishing, Rolling Meadows, 2001).]

S16. Riggs et al. (2006)
CBCL - Child Behavioral Checklist [T.M. Achenbach, *Manual for the child behavior checklist and 1991 profile* (Department of Psychiatry, Univ. of Vermont, Burlington, 1991).]

S17. Raver et al. (2008, 2011)
PSRA - Preschool Self-Regulation Assessment [R. Smith-Donald, C.C. Raver, T. Hayes, B. Richardson, *Early Childhood Quar.* **22,** 20 (2007).]
PPVT - Peabody Picture Vocabulary Test [L.M. Dunn, L.M. Dunn, *Peabody picture vocabulary test- third edition* (American Guidance Service, Circles Pines, 1997).]