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The Potential for School-Based Interventions That Target Executive Function to Improve Academic Achievement: A Review

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This article systematically reviews what is known empirically about the association between executive function and student achievement in both reading and math and critically assesses the evidence for a causal association between the two. Using meta-analytic techniques, the review finds that there is a moderate unconditional association between executive function and achievement that does not differ by executive function construct, age, or measurement type but finds no compelling evidence that a causal association between the two exists.

Keywords: executive function, student achievement, meta-analysis, causal inference

Over the past 10 years, there has been a growing interest in the concept of executive function and the potential for school-based interventions that target executive function to improve academic achievement. In the most general sense, executive function can be thought of as the set of cognitive skills required to direct behavior toward the attainment of a goal. Executive functioning skills enable an individual to (a) prioritize and sequence behavior (e.g., put on pants before putting on shoes), (b) inhibit dominant or familiar responses (e.g., raise a hand rather than just blurt out the answer), (c) maintain task-relevant information in mind (e.g., remember the teacher's request to wash hands and then put on coats before going outside), (d) resist distractions (e.g., listen to the teacher rather than watch other children outside on the playground), (e) switch between task goals (e.g., switch between collecting information for a research report and organizing information into an outline), (f) use information to make decisions (e.g., which history class to take of the four being offered), and (g) create abstract rules and handle novel situations (a skill that is required to solve many math problems). Individuals invoke executive functioning skills whenever they are faced with tasks that require concentration, planning, problem solving, coordination, making choices among alternatives, or overriding a strong internal or external pull (Diamond, 2006).

The ability to direct behavior toward the attainment of a goal is a key to successfully completing most academic tasks. Therefore, it seems intuitive that execution functioning skills would be related to academic achievement. Prior research has documented that students with poor executive functioning skills tend to perform poorly in school (e.g., Gathercole & Pickering, 2000; Swanson & Beebe-Frankberger, 2004), and numerous studies have documented an association between executive function and achievement in both reading and mathematics (e.g., Alloway, Banner, & Smith, 2010; Bull & Scerif, 2001; Clark, Pritchard, & Woodward, 2010; Espy et al., 2004; Gathercole, Pickering, Knight, & Stegmann, 2004). As a result, scholars and practitioners have expressed considerable enthusiasm regarding school-based interventions that target executive function, hypothesizing that an explicit focus on developing executive functioning skills in school could yield substantial gains in student achievement (Barnett et al., 2008; Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008; Blair, 2002; Blair & Razza, 2007; Ursache, Blair, & Raver, 2012).

The concept has also received attention in the popular press with articles about the role that executive function plays in academic achievement appearing in the *New York Times* (Tools of the Mind), the *New Yorker* (the Marshmallow Test), and on National Public Radio (Lehrer, 2009; Spiegel, 2008; Tough, 2009). Yet, despite this enthusiasm, there is surprisingly little rigorous empirical research that explores the nature of the association between executive function and achievement and almost no research that critically examines whether the association is causal. From the existing research it is not clear whether improving executive functioning skills among students would cause their achievement to rise as a result.

Prior Research on the Association Between Executive Function and Achievement

Although there is some debate in the literature about the exact nature of executive function, many researchers believe that it comprises three or four related subcomponents, which include working memory, attention control, attention shifting, and response inhibition (e.g., Hughes, 1998; Miyake et al., 2000; Senn, Espy, & Kaufmann, 2004). Prior research has demonstrated an association between each of these subcomponents and achievement (Blair & Razza, 2007; Gathercole et al., 2004; Raghubar, Barnes, & Hecht, 2010; Yeniad et al., 2013). However, only limited research has explored whether these subcomponents are all equally correlated with achievement. Similarly, much less is known about whether there are differential associations with achievement in reading or math. For example, few studies assess whether some subcomponents are more highly correlated with reading achievement than math achievement or vice versa.

A close look at the studies that do explore the relationship between various aspects of executive function and achievement reveals that they are often contradictory. For example, Espy et al. (2004) found that inhibitory control was more highly correlated with emergent math skills than either working memory or shifting ability, whereas St. Clair-Thompson and Gathercole (2006) found that working memory was more strongly associated with mathematics achievement than was inhibition. Van der Ven, Kroesbergen, Boom, and Leseman (2011) found no significant association between either inhibition or shifting ability and mathematics achievement but found a strong relationship between working memory and achievement in mathematics.

These contradictory findings may be because of a variety factors, including differences in the ages of the samples in each of the three studies (preschool children, vs. 11- and 12-year-olds vs. 7- and 8-year-olds). Current research provides only limited information regarding the association between executive function and achievement as a function of child age. However, because executive function continues to develop throughout the school years, it is quite possible that the association changes over time. These three studies suggest that it may.

The contradictory findings from these three studies may also stem from differences in the measures used to assess the various aspects of executive function or from differences in the size of the samples. Espy et al. (2004) and Van der Ven et al. (2011) included inhibition, working memory, and shifting ability in their models, whereas St. Clair-Thompson and Gathercole (2006) only included measures of working memory and inhibition. St. Clair-Thompson and Gathercole (2006) only included 51 children, whereas Espy et al. (2004) included 96 children, and Van der Ven et al. (2011) had a sample size of 211. Finally, differences may also be because of the methods used to analyze the data. More work is needed to summarize data in a way that accounts for these types of differences across studies so that more definitive statements about the nature of the association between executive function and achievement can be made.

Knowledge about the nature of the association between executive function and achievement is essential so that interventions can be designed to maximize the potential for achievement growth. If the association between executive function and achievement is stronger for mathematics than for reading, for example, then it might make sense to combine programs designed to improve executive function with mathematics curricula or to target such programs to children having difficulty in mathematics. If response inhibition is more closely associated with achievement than attention control or working memory, then maybe school-based programs should be designed to focus more exclusively on that skill. If executive function is more malleable when children are younger or the association with achievement weakens as a child ages, it might make sense to focus resources on preschool and early elementary school programs.

Prior Research on the Causal Link Between Executive Function and Achievement

More important than understanding the nature of the association between executive function and achievement is establishing whether or not the observed association between executive function and achievement is causal. That is, whether changes in executive functions cause changes in achievement. To assess whether the relationship between executive function and achievement is causal, researchers would need to design an intervention that improves a child's executive functioning skills but that does not affect anything else and explore whether that child's achievement improves as a result of exposure to the intervention.

Although the literature demonstrates a strong correlation between executive function and achievement, the two may not be causally related. Executive function could simply be a proxy for other background characteristics of the child, such as socioeconomic status or a parent's level of education, each of which are highly correlated with both achievement and executive function. Researchers have found evidence that both socioeconomic status and family factors are associated with the development of executive functions (Ardila, Rosselli, Matute, & Guajardo, 2005; Li-Grining, 2007; Noble, Norman, & Farah, 2005), so analyses are needed that explore whether executive function is associated with achievement once these background characteristics have been taken into account.

Studies that explore the link between executive function and achievement abound, but what is striking about the body of literature is how few attempts have been made to conduct rigorous analyses that would support a causal relationship. For example, although IQ and executive function are known to be highly correlated, a surprising number of studies fail to control for IQ in their analyses. Many of the studies that do control for IQ do not control for other background characteristics of the child such as parental education or socioeconomic status.

Even fewer studies have randomly assigned children to interventions designed to improve executive function to explore the impact those interventions have on achievement. Yet many researchers cite the link between executive function and achievement as a justification for interventions designed to target executive function in schools (e.g., Bierman et al., 2008; Diamond, Barnett, Thomas, & Munro, 2007; Rabiner, Murray, Skinner, & Malone, 2010; Tominey & McClelland, 2013). Given the severe budget constraints faced by many schools today, it is critical that school leaders invest in programs that have the greatest promise for improving outcomes for children. Although investing in interventions that target executive function as a way to boost academic achievement has strong intuitive appeal, a more critical assessment of the benefits of such interventions is needed before substantial investments are made.

Prior Reviews on Executive Function

Several researchers have undertaken reviews of the literature on executive function in recent years. Some have focused on the degree to which executive function is malleable. Bierman and Torres (in press) described the range of interventions that are designed to influence executive function in school-age children and explore whether or not there is evidence that executive functioning skills improve as a result. They concluded that there is mixed evidence for the malleability of executive function as result of intervention. Similarly, a meta-analysis of working memory training programs conducted by Melby-Lervåg and Hulme (2012) found that such training programs appeared to produce short-term impacts on working memory skills, but they found no convincing evidence that these short-term improvements led to improvements in other skills, including nonverbal and verbal ability, inhibition, word decoding, or arithmetic.

Other researchers have focused on understanding the association between working memory and reading difficulties (Carretti, Borella, Cornoldi, & De Beni, 2009; Swanson & Jerman, 2006) or the relationship between working memory and mathematics (Raghubar et al., 2010). Finally, Yeniad et al. (2013)

conducted a meta-analysis regarding the association between the shifting component of executive function and academic performance. All these reviews found an association between academic performance and the specific executive function under study. Yeniad et al. also found that the association between IQ and achievement was significantly greater than the association between shifting and achievement.

Research Questions

This review builds on existing knowledge in a number of ways. First, rather than focusing on the evidence for the malleability of executive function, this study asks more fundamental questions about the nature of the association between executive function and achievement. The analysis begins with a systematic review of what is known about the unconditional association between executive function and achievement, with an emphasis on exploring variation based on age, achievement outcomes (reading vs. math), and the aspect of executive function under study. Rather than looking closely at a one specific subcomponent of executive function, this review attempts to include a wider range of studies that have explored the relation between executive function and achievement over the past two and a half decades, in an effort to determine whether or not some aspects of executive function are more closely associated with achievement than others. Furthermore, rather than focusing on a specific age group (e.g., preschool) this review explores the relationship between executive function and achievement among all school-age children, to see whether the relationship changes as children mature. In this way this review is able to provide a more comprehensive look at the nature of the association and how it varies than has previously been possible.

Second, this review critically examines the body of research on executive function and achievement to assess the degree to which there is evidence of a causal relationship between the two, a topic that has only been addressed by a handful of researchers (e.g., Willoughby, Kupersmidt, & Voegler-Lee, 2012). Exploring the malleability of executive function is of little value if changes in executive function do not lead to improved outcomes for children. Therefore, we review the most rigorous research regarding the link between executive function and achievement to assess what is currently known about the causal association.

Specifically, this study focuses on the following research questions:

1. What is the unconditional association between executive function and student achievement?
2. Does the unconditional association between executive function and achievement vary by outcome (reading vs. math), the aspect of executive function under study, or the age of the child?
3. Is there evidence of a *causal* link between executive function and achievement? For example, do documented associations hold when strong controls, such as IQ and student background characteristics are included in the analyses? What do studies that randomly assign students to interventions designed to improve executive function tell us about the evidence of a causal mechanism?

To address these questions, we first conduct a meta-analysis in which we systematically review what is known empirically about the association between the various aspects of executive function and student achievement in both reading and math, and then critically assess the evidence for a causal association.

Method

In this section, we describe the methods used in the review, including the definition of executive function that guided our coding, the method of coding and the meta-analytic techniques.

Establishing a Working Definition of Executive Function

Although there is widespread agreement on the general notion of executive function, differences in the ways researchers approach the study of executive function have led to very different operational definitions and approaches to measurement. Researchers differ substantially in the specific dimensions of executive function they identify, and the terms they use to label these subcomponents and in the ways they attempt to measure it. As others have noted, this makes it extremely difficult to synthesize the literature in a meaningful way (Fuhs & Day, 2010; Garon, Bryson, & Smith, 2008; Jurado & Rosselli, 2007; McClelland & Cameron, 2012; Morrison & Grammer, in press).

For this reason, we began the search and coding process for our meta-analysis by establishing a working definition of executive function and rigorously categorizing executive functioning measures according to that definition rather than relying on the varied labels and definitions chosen by study authors. Although some have argued that executive function is a unified concept (e.g., Norman & Shallice, 1986), our working definition is grounded in the work of researchers in the field of child development who postulate that there are three or four partially distinct subcomponents of executive function in children including, inhibition (the ability to ignore distractions and resist making one response instead of another), working memory (the ability to hold information in mind and manipulate it), and cognitive flexibility (the ability to flexibly shift perspectives or the focus of attention; Diamond, 2006).

The view that executive function comprises separable subcomponents is supported by individual difference studies, which have shown that correlations among different executive function tasks are usually low (r = .40) and are frequently not statistically significant (Lehto, 1996; Levin et al., 1996; Lowe & Rabbitt, 1997; Robbins et al., 1998; Schachar, Tannock, & Logan, 1993; M. C. Welsh, Pennington, & Groisser, 1991). This conceptualization is further supported by the work of Miyake et al. (2000) who, in a widely cited article, used confirmatory factor analysis to demonstrate that three components of executive function (inhibition, shifting and updating; i.e., working memory) were partially dissociable from one another. Researchers also point to the variation in the developmental timing of various executive function abilities to further support the notion that the components of executive function are separable (Garon et al., 2008). Recent reviews of the executive functioning literature have used a similar conceptualization (e.g., Banich, 2009; Diamond, 2006; Garon et al., 2008).

We chose to treat executive function as a construct with separate components because we were interested in understanding whether or not these subcomponents had differential relationships to achievement as has been hypothesized in the literature (Blair & Razz, 2007; Espy et al., 2004).

Many researchers identify only three different subcomponents of executive function; working memory, shifting and inhibition and define inhibition as both "the ability to ignore distraction and stay focused" and the ability to "resist making one response and instead make another" (e.g., Diamond, 2006, p. 70). However, other researchers identify a separate construct of attention, which includes both "the ability to ignore distractions" and "the ability to switch focus from one object or task to another," what Diamond (2006) refers to as cognitive flexibility (e.g., Tominey & McClelland, 2011). This conceptualization is supported by Rothbart and Posner (2005) who contend that attention skills are separate from and both underlie and support inhibition skills (Rothbart & Posner, 2005; Rueda, Posner, & Rothbart, 2004).

Measures of inhibition and attention fall into three somewhat distinct categories: (a) tasks that ask individuals to suppress an automatic, prepotent or desirable response in favor of a less dominant response, such as Go-No-Go tasks and Delay of Gratification tasks; (b) tasks that ask individuals to focus on one aspect of a problem and ignore distracting stimuli; and (c) tasks that require individuals to switch flexibly between different aspects of a problem or different decision rules. Thus, we included response inhibition, attention control, and attention shifting as three separate constructs in our categorization. We also combine measures across these various constructs in our analyses, for example, by combining measures of attention and inhibition into a single construct and combining all three (attention, inhibition, and cognitive flexibility) together into one measure to be consistent with various conceptualizations found in the literature.

In establishing these working definitions, we acknowledge that the various dimensions of executive function are highly interrelated and it is often difficult to disentangle them both conceptually and operationally, even in a laboratory setting (e.g., Garon et al., 2008). Most assessment tasks are designed to measure a specific dimension, but it is difficult, if not impossible, to design a task that targets a single dimension in isolation. For example, working memory is often measured by asking individuals to repeat a list of words or numbers in backwards order from memory. However, this task requires not only that individuals remember the words but also that they resist attention to distractors while trying to remember the words (Diamond, 2006). In fact, it is hard to think of a memory task that does not also require an individual to resist attention to distractors or shift set.

For these reasons, as already noted, some researchers view the concept of executive function as a unity construct (e.g., Norman & Shallice, 1986). Therefore, although we categorized measures as rigorously as possible during our search and coding process, we also combine measures across constructs in our analyses below. We also treat executive function as a unitary construct and explore the association between all measures of executive function combined and achievement. Regardless of the way in which we categorize these measures, we find similar results.

Response Inhibition

For the purposes of this analysis, we define *response inhibition* or *inhibition* as the ability to override prepotent or automatic responses. A typical task used to measure this aspect of executive function is the Stroop Color-Word test (Stroop, 1935), in which the individual is first asked to name the ink color of colored patches and then to name the ink color of color words printed in an incongruent ink color (e.g., the word "blue" is printed in red ink). It is difficult to inhibit the impulse to read the word rather than identify the color of the ink. Similarly, the Head-to-Toes task asks children to touch their toes when the assessor says head and vice versa, and the walk-a-line slowly task asks children to walk along a piece of string taped to the floor as slowly as possible—such tasks tap both physical and cognitive aspects of control. Delay-of-gratification tasks, in which a child must wait before doing something he or she desires to do, are also included in this construct.

Attention Control

We define a*ttention control* or *attention* as the ability to focus attention and disregard distracting stimuli—in other words to choose what you pay attention to and what you ignore. Well-developed attention control enables an individual to pay attention to selective aspects of a situation or problem and to maintain concentration. A common task used to measure attention control is the continuous performance task (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956). In one version, the child is presented with familiar pictures on a computer screen and is asked to press a button as fast as possible only when a target picture (chair) appears onscreen. The child must concentrate on identifying the chair when it appears and not be distracted by the other familiar objects.

Although response inhibition and attention control are closely related, in our definition, attention control is distinct from response inhibition in that it is about ignoring distracting stimuli rather than inhibiting a prepotent response. Rather than resisting the desire to do what comes most naturally (i.e., to say "red" when you see the word "red" written in blue ink), it is about blocking out or ignoring irrelevant information (in the case of the continuous performance task, ignoring the other objects that appear). Together, response inhibition and attention control allow individuals "a measure of control over our attention and our actions, rather than simply being controlled by external stimuli, our emotions or engrained behavioral tendencies" (Diamond, 2006, p. 70).

Attention Shifting

We define *attention shifting* as the ability to control and flexibly shift the focus of one's attention while at the same time ignoring distracting information (Zelazo, Carter, Reznick, & Frye, 1997). When trying to solve a problem, an individual must attend selectively to some aspects of a situation and ignore others and shift flexibly between various aspects of the problem. Attention shifting is often assessed using the Stroop Word-Color task. As already noted, in this task an individual is presented with a card in which a color word is presented in an incongruent ink color (e.g., the word "blue" is written in red ink). The individual is asked to either indicate what the word says (i.e., blue) or the color that the word is written in (i.e., red). After several trials the task can be switched—the respondent is asked to name the color instead of the word. The ability to switch back and forth between naming the color of the ink and naming the word on successive trials demonstrates attention shifting. Attention shifting requires both attention control (e.g., the ability to ignore distracting information) and response inhibition (e.g., the ability to inhibit the desire to say the color instead of the word or vice versa) but it is the shifting aspect—the ability to switch back and forth between specified rules that makes attention shifting distinct.

Working Memory

Finally, we define *working memory* as the ability to cognitively maintain and manipulate information over a relatively short period of time. It is related to, but distinguishable from, short-term memory, which is simply the ability to remember information over a short period of time.[1] It can be thought of as the ability to remember information while at the same time engaging in other cognitively demanding activities (Gathercole, Alloway, Willis, & Adams, 2006). Working memory is often assessed using backwards word or digit span tests in which an individual is presented with a list of words or numbers and is then asked to repeat them in the opposite order from which they are presented, a process that requires not only remembering the words or numbers but also reordering them.

Table 1 provides a summary of these constructs, our working definitions, and the tasks commonly used to measure them. In all, we identified more than 60 different measures of executive function in the 67 studies in our meta-analysis. Appendix A (available online at http://rer.sagepub.com/content/by/supplemental-data) indicates how we categorized each of these measures according to our working definition.

Meta-Analytic Sample

We used a variety of techniques to search the literature for studies that measured the association between executive function and achievement in reading or math. First we searched common databases including ERIC, PsycINFO, Web of Science, and ProQuest Dissertations and Theses using the following search terms: academic achievement, math achievement, reading achievement, educational attainment and executive function, executive functioning skills, working memory, attention, inhibition, response inhibition, cognitive flexibility, attention shifting and attention control. We also searched review articles, reviewed reference lists in identified studies, searched the table of contents of relevant journals, and consulted with experts in the field.

Studies were included in our meta-analytic database if they met the following eligibility criteria: (a) the study explored the association between one of the four aspects of executive function defined above and achievement in reading or mathematics, (b) the sample included children between the ages of 2 and 18, (c) the sample did not focus exclusively on students with documented disabilities, (d) the study included at least one continuous and quantitative measure of executive function and at least one continuous and quantitative measure of reading or math achievement, (e) the measure of executive function was obtained via direct assessment (as opposed to teacher or parent report), and (f) the article was published (or for unpublished documents was reproduced) in 2000 or later.

TABLE 1

List of construct definitions and associated measures

Construct	Other names	Definition	Common measure
Response Inhibition	Inhibition, Inhibitory Control	The ability to override proponent, or automatic responses	Stroop Color-Word test: Child is asked to name the ink color of color words printed in an incongruent color (e.g., the word "blue" printed in red)
Attention Control	Attention Monitoring	The ability to focus attention and inhibit the desire to attend to distracting stimuli	Continuous Performance Task: Child is presented with familiar pictures on a computer screen and is asked to press a button as fast as possible only when a target picture (chair) appears onscreen
Attention Shifting	Attention Shifting, Set Shifting, Cognitive Flexibility, Switching	The ability to flexibly shift the focus of one's attention while at the same time ignoring distracting information	Wisconsin Card-Sort task: Child is shown cards with different shapes, colors, quantities, and designs and must discover the "rule" for sorting the cards. During the course of the test the matching rules are changed and the time taken for the participant to learn the new rules, and the mistakes made during this learning process are used to create an overall score
Working Memory	Updating	The ability to cognitively maintain and manipulate information over a relatively short period of time	Backward digit/word span: Child is presented with a list of words or numbers and asked to repeat them in the opposite order from which they are presented

The focus of this article is on the association between executive function and achievement, therefore we only included studies in which the outcome of interest was achievement on a standardized assessment, such as the Peabody Individual Achievement Test, the Wechsler Individual Achievement Test, or the Woodcock–Johnson Tests of Achievement (WJ), or, for younger children, the Test of Preschool Early Literacy or the Preschool Comprehensive Test of Phonological and Print Processing, to name a few. These achievement tests are designed to assess what children know and are able to do academically at a single point in time. A full list of achievement measures is available from the study authors.

Studies in which GPA, homework completion, or teachers' reports of academic performance were the outcome of interest were not included in the sample, because such measures generally assess both scholastic achievement and behavior and the two cannot be disentangled. Although the association between academic behavior and executive function may be important, it is not the direct focus of this article. Studies were also not included if individuals were grouped according to "risk" level, even if risk level was based on test scores, unless the test scores were also used to directly assess achievement.[2] Similarly, we excluded studies in which the outcome of interest was a measure of receptive vocabulary, such as the Peabody Picture Vocabulary Test, because the Peabody Picture Vocabulary Test and other similar measures are often used as a measure of verbal IQ and we did not want to conflate the two outcomes in our study. We did not include studies in which both executive function and achievement were measured but the association between them was not directly explored.

Although much of what has been written about executive function comes from studying individuals with disabilities or those who have suffered brain injuries, we focused on studies of typically developing students. Thus, we excluded any study that looked exclusively at students with documented disabilities. These included studies of children with attention deficit hyperactivity disorder (ADHD), as well as studies that looked at the association between achievement and executive function in children with severe cognitive impairments and/or brain damage. Most (around 85%) of the studies that were excluded, based on this criterion, were studies of students with ADHD. However, we did not exclude studies in which students with ADHD or other documented disabilities were included as a part of a more general study sample; thus, our findings represent what might be expected among a typical group of school-aged children, including some students with ADHD or other documented disabilities.

We limited the sample in this way because we were interested in the potential for school-based interventions focused on executive function to improve the achievement of a general student population. It is likely that the relationship between executive function and achievement in students with ADHD is different than the relationship between executive function and achievement in the general population, and an exploration of this topic was beyond the scope of this article.

Finally, we excluded studies that were published prior to 2000 because the understanding of executive function has advanced considerably over the past decade and a half, in particular the understanding of the development of executive function in children (Garon et al., 2008). This is further supported by the rapid increase in the number of published studies on childhood executive function. A quick literature search for the key words "executive function in children" yields around 6,500 articles in the years between 1999 and 2000, almost 19,000 in the period 2000 to 2009, and 11,000 already this decade.

In accordance with recommended meta-analytic techniques, a study was defined as the exploration of the relationship between executive function and achievement within a particular sample (Lipsey & Wilson, 2001). Thus, some reports (e.g., peer reviewed articles, dissertations) contained multiple "studies" and the same "study" could be reported on in multiple reports. From our search, we identified 67 studies that met the eligibility criteria. These 67 studies included 583 individual correlations between executive function and achievement.

Meta-Analytic Coding

We coded each study along a variety of dimensions. First, we recorded the executive function construct that was being measured and its definition, as well as the measure of executive function that was used. Each measure was categorized according to our working definitions, described above. Assessment tasks that primarily required an individual to ignore distracting stimuli were coded as attention tasks. Tasks that primarily required individuals to suppress a learned or prepotent response (such as naming the color in which a word was written in instead of reading the word) were categorized as inhibition tasks, as were delay of gratification tasks. Tasks that required individuals to shift flexibly between different decision rules were categorized as attention shifting. Backward recall, visual recall, and other complex recall tasks were coded as working memory, as were tasks that required children to remember a series of directions.

Some authors used composite measures of executive function, in which assessments were combined across these categorizations, and others used more global assessments of executive function, such as the Tower of Hanoi, a problem-solving task designed to tap all aspects of executive function. These were coded as general measures of executive function. In instances in which it was unclear how to categorize a particular measure, we looked across studies to see how the measure was most frequently used. The same assessments could be included in more than one category only if there were two different distinct outcomes associated with it. For example, many tasks had both an "inhibit" and a "switch" condition, with different outcome measures for each, and such tasks were included as both response inhibition and attention shifting measures.

For each study we also coded the age of the respondents, the sample size, the measure of achievement used, whether the study controlled for IQ in statistical analyses and if so whether or not the measure of IQ was a verbal or nonverbal measure, and whether other covariates in addition to IQ were included in statistical analyses.

We also coded the type of assessment that was used. Morrison and Grammer (in press) distinguish between laboratory-based measures and measurement in naturalistic settings. Laboratory-based measures attempt to tap discrete cognitive functions such as memory, planning, or attention skills and measure response time or accuracy in response to specific stimuli (Morrison & Grammer, in press). Examples of commonly used laboratory-based tasks include the Wisconsin Card-Sort Task in which children are asked to sort a series of cards first by one attribute (e.g., color) and then by another attribute (e.g., shape) and backward digit or word span tests in which the individual hears a list of words or numbers and is then asked to repeat them back to the assessor in reverse order.

On the other hand, naturalistic assessments are more general assessments of an individual's ability to organize behavior in a goal directed way in contextually relevant situations. Such assessments involve classroom based or "real-world" activities and frequently involve the regulation of emotions as well as cognitions. The ability to walk along a line very slowly, or to whisper the answers to a set of questions are both examples of naturalistic tasks, as are delay-of-gratification tasks. For each executive function measure included in our meta-analytic database we recorded whether the assessment was laboratory based or naturalistic.

Finally, we recorded the unconditional correlations between the measures of executive function and achievement. In some instances we referred to online appendices to obtain the needed information. In cases where information was missing, we wrote to study authors to obtain the missing information. For two studies in the database the authors reported a portion of the relevant correlations as "not significant" and we were not able to obtain the actual correlations from the authors. Rather than impute these correlations as zero, which is often the recommended approach (Lipsey & Wilson, 2001), we omitted them from our analyses. Because these missing data came from studies with relatively small sample sizes, it is likely that the true correlations were much greater than zero, and coding them as zero would risk biasing our results. Because they represented such a small proportion of the total effect sizes in our database (4 out of 583), we felt there was more limited risk of inducing bias if we simply omitted them. Coding was conducted by the authors and two research associates. All coding decisions were reviewed by the lead author.

Meta-Analytic Techniques

To conduct our meta-analysis, we recorded all the unadjusted correlations between reading and math achievement and executive function in the identified studies. Because our effect size measure is a correlation we applied Fisher's *Z*-transformation to the correlations before conducting any computations and then transformed them back prior to presenting results. All correlations were recorded such that better performance on a measure of executive function was positively associated with achievement. For example, in some instances a lower score on a measure of executive function was an indication of better performance and thus was negatively correlated with achievement. These were recorded as positive correlations. Correlations among our 579 effect sizes ranged from a high of 0.87 to a low of −0.14.

Most of the studies in our sample contributed more than one effect size to our database, either because they used multiple measures of executive function, multiple measures of achievement, or because they measured executive function at multiple points in time. Two effect sizes that come from the same study are not statistically independent. Furthermore, there may be dependencies that arise because of shared investigators or laboratories. To account for these dependencies, we clustered all standard errors by lead author, to account for the lack of independence both within study (i.e., the same sample of children) and within investigator.[3] Hedges, Tipton, and Johnson (2010) demonstrate that this method will provide valid standard errors of point estimates, interval estimates, and significance tests as long as the total number of clusters is at least 20 and there is, on average, more than one effect size estimate per cluster. In this analysis, there were a total of 51 clusters with each cluster contributing, on average, 11 effect sizes. Each effect size was weighted by the inverse of the sampling error variance multiplied by the inverse of the number of effect sizes within a study, so that effect sizes that came from larger samples were given greater weight but studies that contributed multiple effect sizes were given less weight in the overall estimation (Gleser & Olkin, 2009; Hedges et al., 2010; Lipsey & Wilson, 2001).[4]

We present average meta–effect sizes separately for reading and math, for working memory, response inhibition, attention control and attention shifting and for ages 3 to 5 years, 6 to 11 years, and 12 to 18 years. In addition, we run regressions that explore the relative contribution of age, subject area and subcomponent of executive function on the overall correlations across studies. To do so we use the following model:

$$\mathrm{ES}_{ij} = \pi_{0j} + \pi_{1j}x_{1ij} + \cdots + \pi_{kj}x_{kij} + e_{ij}, \tag{1}$$

where effect size *i* in study *j* is modeled as a function of the intercept, which represents the average (covariate adjusted) association between executive function and achievement for laboratory-based assessments of working memory conducted on 3 to 5 year olds (the largest category in our sample of studies); *k* independent variables measured at the effect size level $(\pi_{1j}x_{1ij} + \cdots + \pi_{kj}x_{kij})$; and an error term ($e_{ij}$).

Finally, to assess the possibility that publication bias is influencing our findings, we first created a graph in which the sample size was plotted on the *x*-axis and the effect size was plotted on the *y*-axis. The variability in effect sizes should decrease as *n* increases, creating a funnel shaped plot. We find a clear funnel shape in our data suggesting limited evidence of publication bias. Furthermore, for most of our analyses we would have needed a total of 11 or more unpublished studies with effect sizes equal to zero to reduce the effect size from around 0.30 to around 0.20 (Lipsey & Wilson, 2001).

Results

Table 2 provides a descriptive overview of the studies in our sample. Of the 67 studies we identified, 43 explored the relationship between executive function and achievement at a single point in time (e.g., working memory measured at the end of kindergarten and end of kindergarten reading achievement). We refer to these as concurrent associations. Twenty-three of the studies looked at the predictive association between executive function and achievement; that is, they explored the relationship between executive function measured at one point in time and achievement measured at a later point in time. The average sample size among all studies was 237.

More than half of the studies in our sample (57%) were published after 2010, reflecting the rapid increase in interest in the topic in recent years. Most studies focused on children between the ages of 6 and 11 years old (45%) or between the ages of 3 and 5 (35%). Only five studies in our meta-analytic sample (8%) focused exclusively on adolescents or teenagers. Fourteen percent of the studies included children across multiple age categories.[5]

Most of the studies included in the database assessed the association between executive function and achievement in both math and reading (58%); however, it is clear that there is a greater interest in the association between executive function and math achievement than reading. Of the studies we reviewed, 21 (32%) focused exclusively on math as opposed to only 7 (11%) that focused exclusively on reading. Similarly, more attention has been paid to the association between working memory and achievement than any other aspect of executive function; 23 of 67 studies in our sample (35%) focused exclusively on the association between working memory and achievement. The remainder of the studies focused on

TABLE 2

Descriptive statistics for the studies included in the meta-analysis (N *= 67)*

	Number of studies (%)
Predictive studies	24 (35)
Concurrent studies	43 (65)
Published since 2010	38 (57)
Age 3–5	23 (35)
Age 6–11	30 (45)
Age 12–18	5 (8)
Mixed ages	9 (14)
Reading only	7 (11)
Math only	21 (32)
Both reading and math	39 (58)
Working memory only	23 (34)
Response inhibition only	13 (19)
Attention shifting only	1 (1)
Attention control only	3 (5)
Multiple EFs	26 (39)
Naturalistic assessments	14 (21)
Laboratory-based assessments	53 (79)

Note. Average study sample size = 237. EF = executive function.

multiple executive functions (39%), response inhibition (19%), attention control (5%), or attention shifting (1%). Finally, most studies used laboratory-based assessments (79%) as opposed to naturalistic assessments (14%).

Moderate Association Between Executive Function and Achievement

Unconditional Associations

Table 3 presents the unconditional association between executive function and achievement separately for reading and math, predictive and concurrent associations, working memory, inhibition, attention control and attention shifting, age, and measurement type. What is remarkable about this table is how consistent the correlations are regardless of subject matter, age, measurement type, or subcomponent of executive function. The overall average correlation between reading achievement and executive function in our sample is 0.30 and for math it is 0.31. Although it is commonly thought that the association between executive function and math is stronger than for reading, that proposition is not supported by these analyses.

Similarly, the average correlation is essentially unchanged whether you look at the association at a single point in time or in predictive analyses. Even limiting the predictive analyses to those that have a gap of at least 2 years between measurement occasions (e.g., executive function measured in kindergarten and achievement measured in third grade), we find that the meta-analytic correlation is still 0.25 for math

TABLE 3

Unconditional meta-analytic correlations between executive function and achievement

	Reading		Math	
	No. of studies	Meta effect size (95% CI)	No. of studies	Meta effect size (95% CI)
Overall association	44	0.30 (0.24–0.37)	60	0.31 (0.26–0.37)
Concurrent associations	38	0.30 (0.22–0.37)	51	0.33 (0.29–0.37)
Predictive associations	18	0.31 (0.21–0.39)	22	0.30 (0.20–0.39)
3–5 years	22	0.27 (0.20–0.33)	26	0.29 (0.23–0.36)
6–11 years	24	0.36 (0.26–0.45)	34	0.35 (0.28–0.41)
12–18 years	6	0.33 (0.16–0.50)	8	0.33 (0.25–0.42)
Attention control	5	0.21 (0.16–0.25)	6	0.27 (0.22–0.34)
Response inhibition	24	0.25 (0.19–0.31)	33	0.31 (0.25–0.38)
Working memory	25	0.37 (0.29–0.45)	40	0.31 (0.22–0.39)
Attention shifting	11	0.42 (0.30–0.54)	17	0.34 (0.24–0.44)
Other		0.50 (0.28–0.72)		0.47 (0.39–0.55)
Naturalistic measures	13	0.30 (0.16–0.43)	11	0.22 (0.12–0.33)
Laboratory-based measures	38	0.34 (0.28–0.41)	53	0.32 (0.26–0.38)

Note. CI = confidence interval.

and 0.24 for reading, suggesting that the relationship between executive function and achievement remains relatively stable over time.

The associations are somewhat stronger for 6 to 11 and 12 to 18 year olds than for 3 to 5 year olds, which likely reflects the difficulty of reliably assessing executive function among preschoolers. Similarly, the laboratory based assessments are somewhat more highly correlated with achievement, especially in math, than are the naturalistic measures.

Finally, looking at the associations separately by each of the four subcomponents we identified earlier in the article—working memory, response inhibition, attention control, and attention shifting—we find that for the most part the association with achievement is similar across the four subcomponents, although working memory and attention shifting appear to be more highly correlated with reading achievement than attention control or response inhibition.

Meta-Analytic Regressions

To assess whether any of the differences seen in Table 3 were statistically significant we ran a series of meta-analytic regression analyses. The results are shown in Table 4. The first model explores whether the association between executive function and achievement differs across different age groups, measurement type (naturalistic or lab based), achievement measure (reading or math), or measurement occasion (predictive or concurrent). In Model 1, no distinction is made between the various subcomponents of executive function; thus executive function is treated as a unified construct. None of the covariates included in this model

TABLE 4

Meta-analytic regression results

	Model 1, Coefficient (*SE*)	Model 2, Coefficient (*SE*)	Model 3, Coefficient (*SE*)	Model 4, Coefficient (*SE*)	Model 5, Coefficient (*SE*)
Age 6–11	0.05 (0.04)	0.05 (0.04)	0.04 (0.04)	0.05 (0.04)	0.05 (0.04)
Age 12–18	0.03 (0.05)	0.03 (0.04)	0.03 (0.05)	0.02 (0.05)	0.03 (0.05)
Age mixed	0.02 (0.03)	0.01 (0.03)	0.01 (0.02)	0.02 (0.03)	0.02 (0.02)
Naturalistic measures	−0.05 (0.06)	−0.05 (0.06)	−0.04 (0.06)	−0.03 (0.06)	−0.04 (0.06)
Predictive analyses	−0.02 (0.04)	−0.02 (0.04)	−0.01 (0.03)	−0.03 (0.04)	−0.03 (0.04)
Reading	−0.00 (0.02)	−0.00 (0.02)	0.06 (0.03)	−0.00 (0.02)	−0.00 (0.02)
Attention/inhibition				−0.03 (0.03)	
Attention/inhibition/ shifting					−0.02 (0.04)
Attention control		−0.09* (0.03)	−0.04 (0.04)		
Response inhibition		−0.01 (0.04)	0.02 (0.04)		
Attention shifting		0.03 (0.05)	0.02 (0.05)		
Reading * Attention			−0.13** (0.04)		
Reading * Inhibition			−0.11** (0.04)		
Reading * Shifting			0.02 (0.06)		

Note. SE = standard error. Regression analyses include 51 lead authors, 67 studies, and 579 individual effect sizes.
*$p < .05$. **$p < .01$. ***$p < .001$.

are statistically significant, suggesting that the association between executive function and achievement does not vary by age, measurement type, achievement measure, or measurement occasion.

The second model (Model 2) includes the same covariates as Model 1 but adds separate indicator variables for inhibition, attention control, and attention shifting (working memory is the omitted category).[6] In this model, we find that the association between attention control and achievement is significantly lower than for working memory. Furthermore, when we test whether the association is the same for attention control and inhibition variables and attention control and attention shifting variables, we reject the null hypothesis that the associations are equal, suggesting that the correlation between attention control and achievement is lower than for the other three subcomponents of executive function. This finding should be interpreted with caution however, because as is shown in Table 3, there were only five studies in reading and six studies in math that explored the association between attention control and achievement.

We also tested whether the association between any of the four subcomponents and achievement differed by subject matter (reading vs. math). In Model 3, we included not only the same covariates as Model 2 but also interaction terms between the various subcomponents and whether or not the achievement outcome was reading or math. We find that the association with achievement is somewhat lower for measures of inhibition and attention for reading achievement than it is for math.

As described above, it is often difficult to make a distinction between the various subcomponents of executive function—particularly between attention control and response inhibition, we therefore also combined the measures of attention control and response inhibition into a single construct. We then compared the overall association between the combined inhibition/attention measure and achievement with the association between working memory and attention shifting and achievement. The results are shown in Model 4. When the measures are combined in this way, we find no statistically significant difference between the two—the attention/inhibition and the working memory/shifting aspects of executive function are each correlated with achievement at around the 0.30 level.

Finally, we combined the attention control, response inhibition, and attention shifting measures into a single construct and compared them with the measures of working memory. Again, we find no difference in the association with achievement for this combined construct and working memory (shown in Table 3, Model 5).

Evidence for a Causal Relationship: Correlation but No Apparent Causation

As the meta-analytic results indicate, there is substantial evidence that academic achievement and measures of executive function are correlated—both at a single point in time and as predictors of future achievement, and for a variety of different constructs and age groups. Despite this, there is surprisingly little evidence that a causal relationship exists between the two. High levels of executive function may simply be a proxy for other unobserved characteristics of the child.

In this section of the article, we review the evidence for a causal relationship between executive function and achievement. We begin by exploring the evidence for a causal link among the studies included in our meta-analytic database. We then review the handful of studies that have randomly assigned students to interventions designed to improve executive function and explore whether or not increases in executive function that result from these programs lead to improvements in student achievement. This provides another avenue for assessing whether or not a causal association exists.

Limited Evidence for a Causal Link in Our Meta-Analytic Sample

As a part of our meta-analytic coding, we recorded whether any control variables were included in regression analyses that explored the relationship between executive function and achievement, and if so, what they were. The set of control variables included in a study were coded as "strong controls" if they included any type of background characteristics of the child (e.g., maternal education, socioeconomic status, prior achievement, IQ). The set of control variables were considered "weak controls" if they did not account for anything about the child's background or were simply other measures of executive function—for example, age was considered a weak control, as was gender. If the researchers controlled for IQ, we also recorded whether it was a verbal or nonverbal measure, because prior research suggests that the association between executive function and verbal and nonverbal IQ measures differ (Alloway & Alloway, 2010).

Figure 1 displays the number of studies in our meta-analytic sample with various types of controls. Among the 43 concurrent studies in our sample, 25 included weak

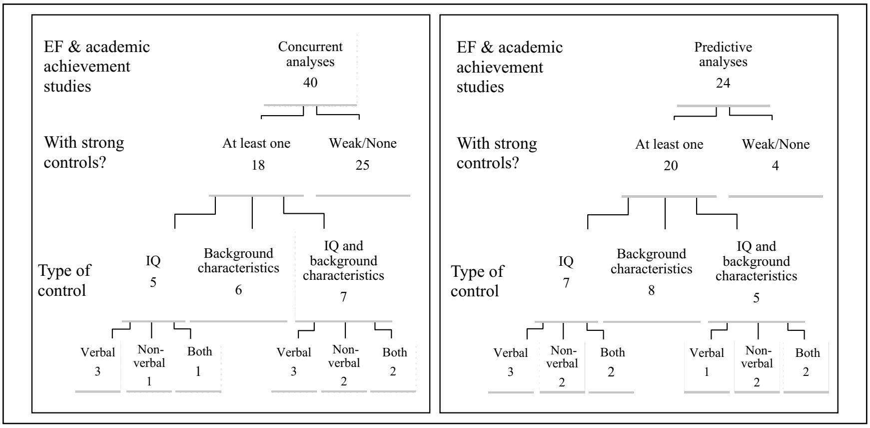

FIGURE 1. *Number of studies in the meta-analytic sample with various types of controls.*

or no controls and only seven controlled for both background characteristics and IQ. Among the 24 predictive studies, only four did not include some type of control variable but only five included both background characteristics and a measure of either verbal or nonverbal IQ. One of the seven concurrent studies did not report the coefficients on the regression results and thus is not included in our discussion below.

The findings from these 11 studies (six concurrent and five predictive studies) are shown in Tables 5 and 6. Table 5 describes the details of each predictive study that included strong controls and includes the unconditional association and the conditional standardized coefficient for each association that was explored. Table 6 shows the same information for the six concurrent studies for which we had usable data.

Predictive associations. We focus first on the predictive associations (Table 5). These five studies reported on nine different associations between executive function and math and four different associations between executive function and reading. Once child background characteristics and IQ are accounted for, the association between executive function and achievement drops by more than two thirds in most of these studies and in most cases the conditional associations are close to zero. Furthermore, the associations are no longer statistically significant. Only one association was positive and statistically significant after covariates were included in regression analysis. Fitzpatrick and Pagani (2012) found a positive and statistically significant association between working memory and achievement in math after controlling for gender, SES, and verbal and nonverbal IQ. However, the covariates included in the Fitzpatrick and Pagani (2012) study were more limited than the other predictive studies listed in the table. The studies which included richer covariates found no positive statistically significant associations after accounting for covariates. One association was statistically significant, but in the wrong direction—in the Duncan et al. (2007) NICHD sample

TABLE 5

Summary of the most rigorous studies exploring the association between executive function and achievement

					Unconditional associations		Conditional associations	
Study	Age	EF construct	EF measure	Controls	Reading	Math	Reading	Math
Clark et al. (2010)	4-year-old EF on 6-year-old achievement	Shifting	FIST	SES, parental report of EF, gender WJ-R passage comprehension, FIST, Shape School-Inhibit, Shape School-Shift, WPPSI-R IQ (verbal and nonverbal)	N/A	.46**	N/A	.15 ($n = 104$)
		Inhibition	Shape School-Inhibitory Control			.41**		.00 ($n = 104$)
		Shifting	Shape School-Switch			.18		.03 ($n = 104$)
De Smedt et al. (2009)	First-grade EF on second-grade achievement	Working memory	Composite of listening span, counting span, and backward digit span	Prior achievement, age, phonological loop, visiospatial sketchpad, Raven's Progressive Matrices (nonverbal)	N/A	.53**	N/A	.09 ($n = \sim 75$)
Duncan et al. (2007) (NICHD)	Preschool EF on fifth-grade achievement	Attention	Continuous performance task, attention	Ethnicity, gender, m. rating of child health, data collection site, birth order, no. of children in home, household structure, m. education, parent education, Reynell Developmental Language Scale (verbal)	.18*	.22*	−.02 ($n = 907$)	−.00 ($n = 907$)
		Attention problems	Continuous performance task, impulsivity		−.20*	−.18*	.05 ($n = 907$)	.06* ($n = 907$)
Liew (2010)	First-grade EF on second-grade achievement	Inhibition	Walk-a-line	Economic adversity, age, gender, ethnicity, prior achievement, teacher support, Universal nonverbal intelligence test (nonverbal)	.14**	.21**	.04 ($n = 791$)	.04 ($n = 791$)
		Inhibition	Task accuracy		.11*	.07	−.01 ($n = 791$)	−.01 ($n = 791$)
Fitzpatrick and Pagani (2012)	2- and 3-year-old EF on K achievement	Working memory	Imitation Sorting Task	Gender, SES, WPPSI-R Block Design, PPVT (verbal and nonverbal)	N/A	.21***	N/A	.13*** ($n = 1,834$)

Note. FIST = Flexible Item Selection Task; m. education = maternal education; EF = executive function; WJ-R = Woodcock–Johnson–Revised; SES = socioeconomic status; PPVT = Peabody Picture Vocabulary Test; WPPSI-R = Wechsler Preschool and Primary Scale of Intelligence–Revised; EF = executive function. The p values for the Duncan et al. (2007) unconditional correlations were all reported simply as $p < .05$, but given the sample size the exact p values were likely much smaller for many of these correlations.

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$.

TABLE 6

Summary of the most rigorous concurrent studies exploring the association between executive function and achievement

Study	Age/grade	EF construct	EF measure	Controls	Unconditional associations		Conditional associations	
					Reading	Math	Reading	Math
Valiente, Lemery-Chalfant, and Swanson (2010)	K	Inhibition	Continuous performance task	SES, gender, parent reported effortful control, sadness, PPVT (verbal)	.13*	.27**	.15* (n = 291)	.15* (n = 291)
Lee, Ng, Ng, and Lim (2004)	Grade 5	Working memory	Digit recall	Literacy, digit recall/counting recall/mazes memory, WISC–III (verbal and nonverbal)	N/A	.52***	N/A	−.04 (n = 151)
			Counting recall			.37**		.21 (n = 151)
			Mazes memory			.40**		.06 (n = 151)
Andersson (2008)		Working memory	Visual-matrix span	Age, reading, counting span, verbal fluency, trail making/visual-matrix span/Stroop tasks/Coris-block span, Raven Progressive Matrices (nonverbal)	N/A	.50*	N/A	.11 (n = 141)
		Shifting	Trail making task			.61*		.17** (n = 141)
		Inhibition	Stroop task			.28*		.03 (n = 141)
		Working memory	Corsi-block span			.33*		.04 (n = 141)
Espy et al. (2004)	2–5 years old	Working memory	Composite: Delayed alteration, six boxes, visual attention subset	Age, m. education, working memory, shifting or inhibition, Picture Vocabulary Test (verbal)	N/A	.31**	N/A	.14* (n = 96)
		Shifting	Spatial reversal			−.08		−.05 (n = 96)]
		Inhibition	Composite: Continuous Performance Test,[a] delayed response, self-control, statue			.55***		.44*** (n = 96)

(continued)

TABLE 6 (continued)

					Unconditional associations		Conditional associations	
Study	Age/grade	EF construct	EF measure	Controls	Reading	Math	Reading	Math
Swanson and Beebe-Frankenberger (2004)	First, second, and third grade	Inhibition Working Memory	Random number and letter generation updating task Listening, sentence span, digit/sequence span, semantic span, semantic association, visual matrix, mapping/ directions	Algorithm knowledge, reading achievement, semantic processing, speed, phonological processing, age, short-term memory, working memory, inhibition, Raven Colored Progressive Matrices (nonverbal)	N/A	–.25*** −.31*** .51*** .54***	N/A	−.02 (n = 353) calc. −.05 (n = 353) word problems .07** (n = 353) Calc. .18** (n = 353] word problems
Gathercole et al. (2006)	6–11 years old	Working memory	Working Memory Battery Test for Children	Language ability, phonological awareness, math/reading achievement, (WISC–III) (verbal and nonverbal)	.56*	.59*	.25 (n = 46)	.18 (n = 46)

Note. m. education = maternal education; TR = teacher/parent report; DA = direct assessment; calc. = calculation; SES = socioeconomic status; PPVT = Peabody Picture Vocabulary Test; EF = executive function; WISC–III = Wechsler Intelligence Scale for Children.
a. We have classified the Continuous Performance Test as a measure of attention elsewhere, but because in this study it is included as part of a composite with three other measures we have classified as inhibition here, as part of the composite.
$*p < .05$. $**p < .01$. $***p < .001$.

students who were more impulsive, as measured by the continuous performance task, were found to have higher math achievement.

In addition, after controlling for background characteristics and IQ in the predictive studies the largest standardized coefficient was .15. A standardized coefficient indicates what a one standard deviation change in the measure of executive function would mean in terms of a standard deviation change in achievement. The most effective school-based interventions designed to influence executive function have only had an impact on measures of executive function equal to around half a standard deviation (e.g., Raver et al., 2011). This means that under the best case scenario (e.g., a treatment impact of 0.50 standard deviations on measures of executive function and a true association between executive function and achievement equal to 0.15) interventions designed to improve executive function would only have the potential to increase future achievement by less than a tenth of a standard deviation (half of 0.15).

The final thing to note about the studies listed in Table 5 is that most of these studies did not control for other aspects of executive function. For example, the studies of inhibition did not control for measures of working memory, attention control, or attention shifting. This is particularly problematic when considering how to develop and target effective interventions, because without controlling of other aspects of executive function it is difficult to pinpoint which aspect should be given the greatest emphasis in the training. If working memory were really the most important contributor to achievement, and working memory and attention have a common component, then the measures of attention might just be proxies for working memory. Under such a scenario interventions designed to improve attention would not necessarily lead to the expected increases in achievement.

Concurrent associations. The six studies that rigorously explored the relationship between executive function and achievement measured concurrently are summarized in Table 6. These six studies explore 14 different associations between executive function and achievement in math and two associations between executive function and reading. For the most part, the findings are the same as the predictive studies. After including covariates in regression analyses, the conditional associations drop by well over a half in most cases. Only six of the 14 associations between math achievement and executive function are statistically significant once IQ and child background characteristics are accounted for. The two analyses that explore the association between executive function and reading achievement remain statistically significant after controls are included.

The concurrent associations tend to be larger than the predictive associations; two of the standardized regression coefficients exceed .40. However, these studies also generally use fewer control variables in their analyses than did the studies that explored the predictive association between executive function and achievement. No clear patterns can be discerned from the results; some studies found a strong and statistically significant association between response inhibition and math (e.g., Espy et al., 2004), but others did not (Swanson & Beebe-Frankenberger, 2004). Some found a strong and statistically significant association for working memory and math (Swanson & Beebe-Frankenberger, 2004). Others did not

(Gathercole et al., 2006). Differences in measurement and method make comparisons difficult. In general, the results are far from conclusive and provide only limited support for a causal relationship.

Limited Evidence for a Causal Link Among Random Assignment Studies

Although regression analyses can be instructive when conducted rigorously, it is only the first step in establishing a causal relationship. The next logical step is to randomly assign a group of children to an intervention that improves their executive functioning skills and see whether children in the treatment group experience higher levels of achievement as a result. We searched the literature to identify random assignment studies of (a) interventions designed to improve executive function skills in children without documented disabilities and (b) which measured the impact of the intervention on both executive function and achievement.

To identify these studies, we again searched common databases including ERIC, PsycINFO, Web of Science, and ProQuest Dissertations and Theses. We used the following search terms: academic achievement, math achievement, reading achievement, educational attainment and executive function training, working memory training, attention training, inhibition training, response inhibition training, and cognitive flexibility training. We also searched review articles, reviewed reference lists in identified studies, searched the table of contents of relevant journals, and consulted with experts in the field.

We identified five studies that met our criteria. Although numerous studies explored the effect of training on executive function skills, most did not explore the impact of the training on achievement, did not use a randomized design or involved students with documented disabilities. The interventions summarized here were not all designed to influence executive function exclusively, but they represent the most rigorous studies available in which the target of the intervention included executive function. We summarize these five studies and discuss what insight they provide regarding the nature of the relationship between executive function and achievement.

Tools of the Mind. The most widely known study was of the *Tools of the Mind* (*Tools*) preschool curriculum in which teachers and students were randomly assigned to the *Tools* program or to control classrooms that implemented a traditional early literacy curriculum. The *Tools* curriculum focuses on improving executive function skills in young children. Teachers reportedly spend up to 80% of their time each day, every day, promoting executive function skills and there are 40 executive function promoting activities done throughout the year, such as play planning and activities designed to promote attention and memory. The program promotes the development of self-regulation skills along with the development of academic skills in an integrated program of activity.

An early study of the *Tools* program, that included 147 children in 24 classrooms who were randomly assigned, found that the *Tools* program had significant impacts on the two measures of executive function that were assessed—the flankers task and the dots task, both of which were designed to tap a variety of executive function subskills (Diamond et al., 2007). *Tools* students performed significantly better than children in the control classrooms on both simple and complex executive function tasks. For example, students in the control group averaged 84% correct on a reverse flankers task, whereas the control group performed near chance (65% correct). The largest effects were found on the most demanding tasks.

Although the impacts on executive function were quite large, there were no baseline measures of executive function, so it is possible that children in the *Tools* condition may have started the school year with higher executive functioning skills. In addition, it is not clear from the description of the analyses whether or not the authors controlled for the clustering of students within classrooms in their analyses, which leaves open the possibility that the differences, despite their magnitude, were not statistically significant. This study showed that the measures of executive function were correlated with achievement among the students in the *Tools* condition but did not explore the impact of the program on achievement.

A follow-up study showed no statistically significant effects of the *Tools* program on achievement once the clustering of students within schools was taken into account (Barnett et al., 2008). A more recent study, that included baseline and post-intervention testing, randomly assigned 60 preschool classrooms in five districts to the *Tools* curriculum or an "as is" control group. That study found no impact of the *Tools* program on six different measures of executive function (dimensional card sort, copy design, forward span, backward span, peg tapping, and Head-to-Toes tasks), and a small positive impact for the *control group* on three of seven achievement measures (Farran, Wilson, Lipsey, & Turner, 2013). Despite the wide publicity the program has received, a careful read of these studies suggests no compelling evidence of a positive impact on executive function and no evidence of a positive impact on achievement for the *Tools* program.

Head Start REDI. A second study explored the impact of the Head Start REDI program on executive function and achievement. In that study, 44 classrooms were randomly assigned to the REDI program or to a "practice as usual" condition. Head Start REDI is a preschool program designed to help children enter school ready to learn by fostering better engagement with school and reducing disruptive and off-task behaviors. The intervention promotes the development of language skills, emergent literacy, prosocial skills, emotional understanding, self-regulation, and aggression control. Social-emotional skills, including self-regulation skills, were taught through a series of weekly lessons and extension activities from the Promoting Alternative THinking Strategies curriculum. Head Start teachers were trained on the Promoting Alternative THinking Strategies curriculum and mentored on generalized teaching strategies to promote social-emotional development, including positive classroom management, use of specific teacher praise and support, emotion coaching, and induction strategies to promote appropriate self-control.

Children were then assessed on a variety of outcomes at the beginning and the end of the year. After controlling for child gender, race, age, nonverbal cognitive ability, and pretest scores, the researchers found a significant effect of the REDI intervention on two of the five measures of executive function that were assessed—a dimensional card sort task ($p = .06$) and an attention/impulsivity measure ($p < .05$) based on assessor report of the child's behavior during the assessment, with effect sizes of .20 and .28, respectively. No impacts of the intervention were found on a backward word span task, a walk-a-line slowly task, or a peg tapping task. The intervention also had a positive impact on the two measures of early literacy skills that were assessed: print awareness and phonological sensitivity, with effect sizes of 0.18 and 0.43, respectively.

The authors then explored whether improvements in the measures of executive function mediated the relationship between the intervention and achievement. They did so by first estimating the impact of the program on achievement without accounting for end of the year executive function scores and then estimating the impact again, this time controlling for end-of-the-year executive function scores. The difference between these two estimates was considered the degree to which the executive functioning measures mediated the impact on achievement. They found that the combined impact of the intervention on the two executive function measures accounted for 16% and 33% of the impact of the intervention on the measures of phonological sensitivity and print knowledge, respectively. When examined separately, the dimensional card sort task was not a significant mediator of the intervention effect on either of the outcomes, however the assessor report of attention/impulsivity was a significant mediator of the intervention effect on phonological sensitivity and a marginally significant mediator of the intervention effect on print knowledge.

Unfortunately, this analysis does not shed any definitive light on whether or not the association between executive function and achievement is causal, because the REDI intervention targeted executive function and achievement simultaneously. It is quite plausible that the measures of executive function are simply serving as proxy for all the other factors that were affected by the treatment but were not included in the model. For example, if the intervention improved children's ability to take tests, then children would perform better on both measures of executive function and on measures of achievement. If the improved ability to take tests was not accounted for in the analyses, the improvement in executive function would be correlated with the improvement in achievement. Yet it would not be the improvement in executive function that led to the increased achievement but rather the better test taking skills. It is also possible that improvements in achievement lead to improvements in executive function and not the other way around. Thus, we learn little about the causal association between executive function and achievement from this study.

This is not to suggest that simultaneously targeting both achievement and executive function is not an appropriate way to intervene; in fact focusing on both academic outcomes and executive functioning skills is likely an effective way to approach such programs. However, studies of such programs cannot provide rigorous evidence regarding the causal nature of the association between executive function and achievement.

At the same time, changes on the assessor report were the strongest predictors of changes in achievement. However, because the assessor report was completed immediately after the administration of the child's assessment battery, it is likely that at least part of the association is because of the fact that students who were having a "good test day" both performed better on the academic assessments and were also rated more highly by the assessor. Under such a scenario, it is the good night's sleep, the good breakfast, or the other factors that resulted in a "good test day" that account for the association, not the change in executive functioning skills.

Chicago School Readiness Program. A third study, the Chicago School Readiness Program (CSRP) program, randomly assigned 18 sites (with a total of 35 preschool classrooms) to either the CSRP program or to an "as is" control condition and students' executive function and academic skills were assessed, pre- and postintervention. The CSRP is a preschool program designed to influence children by providing teacher professional development and support around establishing a well-regulated classroom, thereby improving child self-regulation, executive function skills, and achievement. The intervention included five 6-hour training sessions for teachers that focused on classroom management and ways to improve the relationship between students and teachers, as well as a mental health consultant who met with teachers weekly to provide support, help reduce stress and assist teachers in implementing positive classroom management techniques.

The authors found significant impacts on two of three measures of executive function assessed, including a composite response inhibition measure (balance beam and pencil tap), and the same assessor report of attention/impulsivity used in the Bierman et al. (2008) study, with effect sizes of 0.37 and 0.43, respectively. A behavioral composite measure of response inhibition, which included a variety of delay-of-gratification tasks (toy wrap, toy wait, snack delay, and tongue test) was not statistically significantly affected by the program but had an effect size of 0.20. The study also found impacts on emerging academic skills, with an effect size of 0.63 on letter naming and an effect size of 0.54 on early math skills.

In mediational analyses the authors estimated the impact of the program on the measures of executive function, estimated the impact on the measures of school readiness, and then computed the product of those two estimated impacts. They found that both the response inhibition measure and the measure of attention/impulsivity were statistically significant mediators of the intervention effect on both letter naming and early math, however the behavioral measure of response inhibition was not.

This study provides compelling evidence for the malleability of executive function skills using a school-based intervention, as well as the potential for high-quality preschool programs to improve academic achievement and school readiness but suffers from the same drawbacks as the REDI study—the intervention was designed to influence both executive function and achievement simultaneously and therefore sheds no light on whether the association between the two is causal.

In order to definitively establish a causal link between executive function and achievement, we would need to find an intervention designed to influence executive function that did not directly influence achievement, randomly assign that intervention to students and assess both their executive function and achievement at the end of the intervention. If impacts were observed on the measures of executive function and on measures of achievement, the observed impacts on achievement could then be attributed to the improvements in executive function. We identified two studies which had this potential.

Red Light, Purple Light. The first intervention tested the impact of the *Red Light, Purple Light* program on executive function and achievement (Tominey & McClelland, 2011). The *Red Light, Purple Light* intervention was a preschool-based pull-out program in which children participated in bi-weekly playgroup sessions designed to improve their behavioral self-regulation. The sessions involved playing games such as Red Light, Purple Light—which is similar to the traditional Red Light, Green Light game, but in which the students had to remember which color meant "stop" and which meant "go" and the rules were changed periodically, so that sometimes purple indicated "stop" but other times it meant "go." There were six different games of this type and students participated in the play groups two times a week, for 30 minutes each session, over a period of 8 weeks.

Children were randomly assigned within classrooms to either the *Red Light, Purple Light* intervention or to an "as is" control group. A total of 65 children participated in the study (28 treatment and 37 control). Students were assessed at baseline and again, after the conclusion of the intervention. Executive function was assessed using the Head-Shoulder-Knee-Toes (HTKS) task. Achievement was assessed using the WJ–III letter-word identification, applied problems, and picture vocabulary subtests. The authors found no impact of the intervention on the HTKS task for the full sample, but found a small, statistically significant impact on those who started the year with the lowest HTKS scores, with an effect size equal to 0.34 ($p < .05$). They also found a statistically significant impact of the intervention on the letter-word identification subtest, but not the applied problems or picture vocabulary test, for the full sample. The impact on achievement was not assessed in the subsample that started the year with the lowest HTKS scores.

It is somewhat puzzling that the program appeared to impact achievement but not executive function in the full sample. There are several possible explanations. First, the impact on executive function among those with the lowest initial HTKS scores may have been driving the achievement results in the full sample. Similarly, small but not statistically significant gains in executive function among the full sample may have contributed to improved achievement. It is also possible that the intervention was actually influencing students' executive function but in ways not detected by the HTKS task. The study would have been stronger had more measures of executive function been obtained. The intervention may also have had an impact on factors other than executive function, such as improved self-confidence, and it may have been those factors, not executive function, that influenced achievement. Finally, the achievement results observed may have been spurious—the impact was small and was only observed in one of the three measures of achievement assessed. Given the range of possible interpretations this study does not shed much light on the nature of the relationship between executive function and achievement.

Computerized attention training. The second and most compelling study we identified compared computerized attention training, computerized academic support, and a waitlist condition and assessed the impact of each on teacher rated attention and a direct assessment of academic achievement (Rabiner et al., 2010). Seventy-seven first graders in five public schools who were identified by their teachers as having attention problems were randomly assigned to one of the three conditions (computerized attention training, computerized academic support, or waitlist). The computerized attention training involved a set of 10 exercises that focused on training auditory and visual sustained attention. For example, children played a game in which they were instructed to press the space bar each time a certain symbol appeared and refrain from responding to all other stimuli that appeared on the screen. Another activity involved listening to first one and then a second sequence of tones and deciding whether or not the two sequences were the same. The computerized academic support program, on the other hand, taught specific reading and math skills in short, self-paced units, with frequent and immediate feedback. The students participated in the computer training (either attention or academic support) in groups of 4 to 6 students, two afternoons per week for 14 weeks and were monitored by researchers and school staff.

Attention was assessed at baseline and post-intervention using the Connors Teacher Rating Scale-Revised (CTRS-R). Achievement was assessed using the WJ–III Broad Reading and Broad Math scores and the DIBELS reading fluency test. Both the attention training and academic training groups showed improvements on the CTRS-R, but the impact was greater for the academic training group. The percentage of students in the academic training program that improved by more than 0.5 *SD* on the CTRS was 56, compared with 44% for the attention training group and only 16% for the waitlist condition. Only the academic training group showed any impacts on the tests of achievement. There was a statistically significant difference on the DIBELS fluency test for the academic training group. Of those participating in the academic training, 67% improved their DIBELS scores by at least 0.5 *SD* compared with only 40% of the control group and 44% of the attention training group. The study found no long term effects on attention and did not explore the long-term effects on achievement.

This study suggests that there may not be a causal relationship between attention and achievement. Although students in the attention training group showed improvements on teacher ratings of attention, they did not show any improvements in achievement. On the other hand, it does suggest that improvements in attention can be obtained via interventions designed to improve achievement. If the goal is to reduce the problem of inattention and increase achievement, separate attention training programs may not be needed. Of course it is possible that the impacts on attention in the computerized training group were simply not large enough to influence achievement. Furthermore, this intervention only targeted attention and therefore does not shed any light on the potential for a causal association between achievement and other areas of executive function, such as working memory.

Discussion

Our meta-analysis indicates that there is a moderate unconditional association between executive function skills (defined and measured in a variety of different ways) and achievement at both a single point in time and as a predictor of future achievement. We find that the overall unconditional association between executive function and achievement is around 0.30 and remains approximately the same for different age groups (3–5 year olds, 6–11 year olds, or 12–18 year olds), different subcomponents (inhibition, attention control, attention shifting, and working memory), and different measurement types (naturalistic vs. laboratory based). Despite common assumptions, we find only limited evidence that the association between executive function and achievement is stronger for mathematics than for reading. When we examine an overall measure of executive function (rather than the subcomponents) we find no difference in the association between executive function and reading or math achievement. Exploring the associations separately by subcomponent, the association between executive function and achievement in math appears to be stronger for attention control and inhibition but not for working memory or attention shifting.

Limited Evidence of a Causal Relationship

At the same time, a careful look at the literature finds no compelling evidence that these associations are causal. We find only five studies that explore the predictive association between executive function and achievement that rigorously control for child background characteristics and IQ. These five studies explore a total of 13 different associations between executive function and achievement and only one association is positive and statistically significant after covariates are included in the regression model. We identified only seven concurrent studies that rigorously controlled for background characteristics and IQ and fewer than half of the associations remain statistically significant after controls were included. In almost all cases the standardized effect sizes drop by more than half, compared with the unconditional correlations. The small number of such studies (we identified only 12 among the 67 included in meta-analysis), suggests that much more work is needed to establish that a causal relationship between executive function and achievement exists.

The few random assignment studies which rigorously evaluate interventions designed to impact executive function provide some evidence that executive function can be influenced by intervention (most of the studies we reviewed showed some positive impacts on measures of executive function) but provide no compelling evidence that impacts on executive function lead to increases in academic achievement. Although several interventions found positive impacts on achievement, these studies all involve interventions designed to influence executive function and achievement simultaneously, and as a result there is no way to determine if changes in executive function led to observed increases in achievement. The one study we reviewed that targeted executive function skills via a computer-based attention training program, and did not target achievement directly, found a reduction in inattentive behavior as reported by teachers but no impact on achievement.

Study Limitations

We have attempted to be as comprehensive as possible in this review, however it has several limitations. First, both for substantive reasons and to limit the scope of the review, we did not include any studies aimed at exploring the link between executive function and achievement in students with documented disabilities. Looking at the wide range of studies that explore the association between executive function and achievement in children with disabilities may yield different conclusions with different implications. Furthermore, this review only explores the association between measures of executive function and achievement as measured by standardized test scores. It does not explore the potential impact of improving children's executive functioning on other schooling outcomes, such as grades, attendance, or drop-out, all of which are important in their own right, or on other important child outcomes, such as behavioral problems or delinquency.

Implications

This analysis is an attempt to systematically frame and critically examine the relationship between executive function and achievement across a disparate literature. Among other things, the findings suggest that more work is needed to establish a causal link between executive function and achievement. Although the link between the two may well be causal, the link should be more clearly established before programs designed to improve executive function in school-age children are taken to scale.

In general, more rigorous research is needed to better understand the relationship between executive function and achievement. More studies that include strong sets of controls for child background characteristics and especially that include measures of the various subcomponents of executive function in the same regression are needed so that the relative impact of each can be explored. Although a number of the more rigorous studies we identified came from large, longitudinal data sets, such data sets are not necessary to conduct rigorous explorations of the association between executive function and achievement. In fact, there were many studies included in this meta-analysis that collected data on background characteristics and measures of IQ but did not control for either or both these factors in their regression analyses. A substantial amount of further investigation could be conducted with existing data sets, which would add considerably to the knowledge base.

Most important, more random assignment studies of programs designed to improve executive function, but which do not simultaneously target achievement, are needed to test whether changes in executive function are causally related to changes in achievement.

Finally, to further the understanding of the link between executive function and achievement, the definitional and measurement problems that plague the study of executive function will need to be resolved. Without a set of clearly defined terms and a consistent set of measures, it will be very difficult to come to any definitive conclusions about how executive function relates to any outcomes of interest. It will also be hard to intervene in ways that benefit children if clear definitions of executive function cannot be identified. The working definitions used here are not perfect, but a similar framework for defining and categorizing the various aspects of executive function is needed to gain greater insights into the potential for executive function to improve outcomes for children.

Notes

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[1]Some researchers also include short-term memory as a component of working memory or make distinctions between complex working memory and simple working memory, which is akin to short-term memory (e.g., Baddeley & Hitch, 1974; Best & Miller, 2010).

[2]There were only a handful of studies in which students were grouped by risk level, and we were not able to obtain individual test scores.

[3]The decision was made to cluster by lead author because this accounted for most of the shared investigators in our sample and at the same time offered a clear decision rule for clustering.

[4]In analyses not shown here, we also allowed each study to only contribute one averaged effect size, with similar results.

[5]All the studies that included predictive analyses measured executive function in preschool, kindergarten, or first grade and used those measures to predict later achievement. The ages reported here are the ages when achievement outcomes were measured.

[6]The omitted category also includes a handful of studies that used composite measures of executive function.

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