Developing Together: The Role of Executive Function and Motor Skills in Children's Early Academic Lives

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A considerable body of research indicates that children's executive function (EF) skills and related school readiness constructs are important for early learning and long-term academic success. This review focuses on EF and a related construct, motor skills with a focus on visuo-motor integration, as being foundational for learning, and describes how these skills co-develop in young children in bidirectional and synergistic ways. The review discusses definitional and conceptual issues, connects EF and visuo-motor integration to relevant theoretical perspectives, discusses measurement issues and advancements, and reviews intervention evidence to support the malleability of these skills in young children. Discussion emphasizes how these skills develop together and suggests that research examining children's learning from a co-development perspective can help promote children's health and well-being.

Young children experience considerable excitement as they move from preschool into more formal school settings like kindergarten in the United States. For many children, this transition goes well, but it can be quite challenging and stressful for others, especially those without the skills to navigate effectively school settings and learning environments. The fact that as many as half of children enter kindergarten with poor school readiness skills (Rimm-Kaufman, Pianta, & Cox, 2000) is one reason for the considerable focus on helping children enter schooling equipped with the skills they need to succeed. Most researchers agree that a combination of skills that include language, executive function (EF), social-emotional skills, early literacy and math skills, and visuo-motor integration skills all help children be successful as they enter formal schooling (Snow, 2006). The role that each of these skills plays and which skill should be the primary target of preschool intervention are still debated, however.

This review examines the role of EF and related school readiness constructs, with an emphasis on motor skills and specifically, visuo-motor integration, in the context of children's transition to kindergarten. A growing body of evidence points to the importance of EF and visuo-motor integration for academic success, perhaps because of their role in helping children succeed in structured learning environments. We discuss definitional and conceptual issues, connect these two constructs to relevant theoretical perspectives, discuss measurement concerns and advancements in this area, and synthesize intervention evidence to support the malleability of these skills in young children.

Our central argument is that EF and related cognitive skills—including what are typically thought of as motor skills—are pre-requisite for children's early learning. They provide a foundation for their long-term academic success, and co-develop in young children in bidirectional and synergistic ways. The theoretical framework for this argument stems from dynamic systems perspectives, which views children's development as multilevel, interactive, and bidirectional (McClelland, Geldhof, Cameron, & Wanless, 2015).

Definitional Issues in EF and Motor Skills

Here and elsewhere, we and others have argued that EF is a foundational cognitive skill (Blair & Raver, 2015; Cameron, in press; McClelland & Cameron, 2012; McClelland et al., 2015). The term "foundational" suggests the role of EF in facilitating the acquisition of academic skills (Beery & Beery, 2010) in easing the process of learning to read or to count, for example. Foundational skills may be less likely targets of explicit instruction, but are nevertheless critical for children to succeed in school settings because they represent the underlying processes of learning. For example, in school readiness assessments, early childhood experts recommend moving beyond static outcomes of what was already learned to incorporating the dynamic processes by which children learn (Hirsh-Pasek, Kochanoff, Newcombe, & de Villiers, 2005). Yet this shift is difficult given that even among adults, cognitive processes are invisible, dynamic, and context-dependent (Ackerman, 1987). For young children, although maturational changes play a key role, cognitive processes can also be highly variable (Diamond, 2002; McClelland et al., 2015). Skills other than EF can also be considered foundational, based on our tri-part definition that foundational skills are: (a) not explicit targets of instruction, (b) represent less visible cognitive processes, and (c) fundamental for learning in one or more content areas. For example, using three large datasets, Grissmer et al. (2010) identified teacher-rated attention as part of EF, fine motor skills, and general knowledge as three under-examined foundations of learning (see also Cameron, Cottone, Murrah, & Grissmer, 2016).

Executive Function (EF)

EF has been highlighted as a construct that is ubiquitous in the lives of young children and significantly predicts a range of short- and long-term outcomes (Blair & Razza, 2007; McClelland, Acock, Piccinin, Rhea, & Stallings, 2013; Moffitt et al., 2011). For example, children use EF when they focus their attention on a puzzle, remember the steps in completing the puzzle, switch attention when their caregiver or teacher tells them to do something else, and demonstrate inhibitory control to stop and put away the puzzle before it is finished. EF is also used when children must persevere to finish the puzzle before playing with a new and attractive toy. Although these examples are small parts of children's everyday routines, they illustrate the foundational importance of EF, which helps children learn to control their thoughts, feelings, and behaviors to solve problems, to plan, and to complete tasks.

Despite debate on the nature of EF among young children, there is general agreement that EF includes the cognitive processes that children need to pay attention and switch focus when needed (cognitive flexibility), remember instructions (working memory), and demonstrate self-control (inhibitory control) (Best & Miller, 2010; Zelazo, 2015; Zelazo, Blair, & Willoughby, 2016). Together, these aspects of EF strongly predict later learning and success and lay the foundation for children to successfully take in and process academic material (Blair & Razza, 2007; McClelland et al., 2013; McClelland et al., 2007). The cognitive components that comprise EF stem from neural circuits in the prefrontal cortex (PFC). The PFC develops rapidly in the early childhood years as children engage in experiences that utilize and strengthen EF skills over time (Shonkoff & Phillips, 2000). It is precisely during this time that children experience increasing attentional and behavioral demands within their early learning environments, which highlights the importance of providing experiences that support the adaptive development of EF (Blair & Raver, 2012; Blair & Raver, 2015).

In addition to EF, constructs such as self-regulation, self-control, and effortful control draw on many of the same underlying cognitive components. These different terms are often driven by discipline-specific terminology (Gagne, 2017; McClelland et al., 2015) but there are also some key differences. For example, *self-regulation* has been often used in developmental psychology and can be seen as an overarching construct that incorporates a broader set of social-emotional and cognitive skills, whereas EF has been argued to be a set of deliberately engaged cognitive processes that enable self-regulation (Blair & Raver, 2015; Zelazo et al., 2016). The term *self-control* has been used in the personality literature to refer to the ability to control emotions and delay gratification (Gagne, 2017; Mischel et al., 2011). Finally, *effortful control* stems from the temperament literature and refers to aspects of inhibitory control, attention, and temperamental characteristics related to children's constitutionally-based ability to manage their reactivity and regulation (McClelland et al., 2015). We also acknowledge that regulatory processes beyond EF, such as self-regulation, self-control, and effortful control, as well as communication skills such as vocabulary and language, are all at play in a successful school transition.

Motor Skills

Motor skills are not typically considered under the umbrella of cognition, but the term "motor" actually implies cognition given that carrying out the physical movements needed for learning require planning and deliberation (Adolph, 2005; Willingham, 1998). Both fine and gross motor skills undergird school functioning, with fine and visuo-motor skills used in pre-academic classroom tasks such as crayon- and pencil-gripping, paper- and materials handling, and symbol recognition (Cameron et al., 2012; Marr, Cermak, Cohn, & Henderson, 2003). The visuo-motor integration aspect of fine motor skills involves coordinating visual perceptions with motor movements and has been positively linked to literacy and mathematics outcomes in a growing number of samples (Cameron et al., 2012; Carlson, Rowe, & Curby, 2013; Grissmer et al., 2010). And gross motor skills help children to literally navigate the classroom, including maneuvering their bodies and learning materials, and to participate in outdoor and play activities. Gross motor skills are implicated in social and behavioral outcomes, in part through children's self-confidence (Skinner & Piek, 2001).

Importance of EF for Early Academic Achievement

To benefit from learning opportunities, children need to have the components of sustained and flexible attention, inhibitory control, and working memory in place. In early childhood, curricula tend to emphasize early reading, writing, and mathematics (Bassok, Latham, & Rorem, 2016; Connor, Morrison, & Slominski, 2006) and foundational skills such as EF help children make progress in these areas.

EF and Reading

EF and its component processes are centrally involved in literacy (Becker, Miao, Duncan, & McClelland, 2014; Cameron, in press; Connor et al., 2016; McClelland et al., 2014). Learning to decode and comprehend text requires inhibitory control to persist through challenge; cognitive flexibility to learn all the associations between letter forms and sounds, and word meanings; and working memory to combine sounds into words and combine words into paragraphs. As students advance in school, EF measures predicts comprehension rather than decoding (Connor et al., 2016; Fuhs, Nesbitt, Farran, & Dong, 2014; Seigneuric & Ehrlich, 2005). This reflects EF's role when tasks are new and not yet automated, and require deliberate attention (Blair, Protzko, & Ursache, 2011).

EF and Writing

EF has been robustly linked to decoding and comprehension aspects of literacy over the school transition, but there are relatively fewer studies on relations between EF and writing. The research that exists, however, has found that aspects of EF (e.g., attention) significantly predict early writing development (Hooper et al., 2011; Kent, Wanzek, Petscher, Al Otaiba, & Kim, 2014; Kim, Al Otaiba, Sidler, & Gruelich, 2013) and that students who struggle with writing are also more likely to have lower EF (Hooper, Swartz, Wakely, Kruif, & Montgomery, 2002). Thus, similar to early reading development, research supports the notion that children who can demonstrate strong EF (e.g., can focus and pay attention) are more likely to develop stronger writing skills.

EF and Mathematics

EF and its components are also strongly and consistently associated with children's mathematics skills throughout early schooling (Blair, Ursache, Greenberg, & Vernon-Feagans, 2015; Clark, Pritchard, & Woodward, 2010; McClelland et al., 2014; Purpura, Schmitt, & Ganley, 2017). Acquiring mathematics competence means learning symbols and their meanings, and being able to shift flexibly between them—for example, grasping that the Arabic numeral "3" and three dots mean the same thing (Kim & Cameron, 2016; Lee, Ng, & Ng, 2009). Inhibitory control and working memory help children manipulate and compare quantitative concepts, learn new concepts, and inhibit incorrect responses or processes, such as adding two numbers that should be subtracted (Bull, Espy, & Wiebe, 2008; Purpura et al., 2017). Similar to how EF supports decoding among younger readers and comprehension among older readers, EF is involved in those aspects of mathematics that are not yet automated. This explains EF and especially, working memory's prominent role in word problems, which require students to retrieve stored content knowledge, such as how many ounces are in a pound, along with cognitively manipulating the quantitative concepts in the problem (Fuchs et al., 2010; Purpura et al., 2017).

Motor Skills and Early Academic Achievement

In addition to EF, motor skill development provides a foundation for children to acquire academic content in early childhood classrooms. These skills enable children to effectively manage their physical environment and learning materials.

Motor Skills and Reading

The investigation of links between motor skills and reading has a long history. In the 1960s and 70s, based on the importance of cognitive test results for academic achievement (Keogh & Smith, 1967), interventionists attempted to remediate reading difficulties with perceptual motor activities (O'Donnell & Eisenson, 1969). This approach was soon dismissed given the weakness of initial research designs and the lack of follow-up experimental evidence (Hammill, Goodman, & Wiederholt, 1974). Since the mid-2000s, the possible importance of motor skills in reading outcomes has resurfaced because large-scale analyses of multiple datasets within and outside the U.S. indicate robust connections between fine motor measures and reading composites that include both decoding and vocabulary (Grissmer et al., 2010; Son & Meisels, 2006). Subsequent research on fine motor skills and literacy has focused on visuo-motor integration. While controlling for EF, visuo-motor integration measures are uniquely predictive of early print knowledge among preschoolers (Cameron et al., 2015), and of letter-word identification, print knowledge, and phonological awareness improvement among kindergarteners (Cameron et al., 2012).

Motor Skills and Writing

Another role for motor skills appears with those aspects of literacy learning that involve orthography, or the visual representations of language through written symbols. This conclusion is consistent with research that has illuminated a close coupling between early writing and reading development (Clark, 2010; Ho, 2011; Juel, 1988; Puranik, Lonigan, & Kim, 2011), with motor skills forming a foundation for writing (Berninger et al., 1992). Several processes in emergent literacy implicate motor skills, especially concepts of print and emergent writing (Beery & Beery, 2010). Sitting at a desk or other surface to read or write requires gross motor skills because children must sit upright and manage the book or paper with one hand and (when writing), the writing utensil with the other (Cameron, in press). Visuo-motor integration, commonly assessed with form-copying tasks such as the Beery VMI, is strongly positively correlated with children's handwriting skills (Ho, 2011) and writing in general for 7- to 15-year-olds (Carlson et al., 2013).

Motor Skills and Mathematics

Visuo-motor integration is also linked to mathematics (Carlson et al., 2013), at times more strongly and consistently than to literacy (Beery & Beery, 2010). Setting up a math problem in writing requires the ability to spatially represent the steps required to solve the problem, to visuo-spatially align numbers, and to write out the answer. Thus, doing early mathematics requires fine and gross motor skills because of close links among math and spatial skills (Cameron, in press) and the role of manipulatives in kindergarteners' math learning (Guarino, Dieterle, Bargagliotti, & Mason, 2013). There is also some evidence that fine motor coordination, or the ability to trace in between lines without making mistakes, is tied to mathematics through its contribution to developing visuo-motor integration (Kim, Duran, Cameron, & Grissmer, 2017). In other words, the simpler skill of motor coordination may serve as a foundation for the more complex motor skill of visuo-motor integration, which in turn provides a foundation for mathematics.

Dynamic Systems Theories, Automaticity, and Reciprocity

Perspectives such as Relational Developmental Systems (Overton, 2015), the Developmental Psychobiological perspective (Blair & Raver, 2015; Gottlieb, Wahlsten, & Lickliter, 2006), and Dynamic Systems Theories (Thelen & Smith, 2006), reflect current perspectives in the field of Developmental Science. These perspectives are especially useful in understanding the dynamic relations between children's developing EF, motor skills, and other cognitive and academic skills. Key concepts related to these perspectives include *probabilistic epigenesis* and *experiential canalization*. In addition, the theory of *automaticity* and the concept of *reciprocity* illustrate how probabilistic epigenesis and experiential canalization emerge.

Probabilistic Epigenesis and Experiential Canalization

Probablistic epigenesis describes the active and ongoing interaction of children's biology and environment that contributes to individual differences in children's EF and motor skill development (Gottlieb et al., 2006). Within this framework, experiential canalization is the dynamic process through which these coactions between children and their environment can gradually promote some paths over others. For example, a child who is temperamentally inhibited *and* has poor motor skills may withdraw from physical activities early in schooling, which may contribute to low self-worth and challenges developing appropriate social skills (Cameron, in press). For such a child, an early intervention that successfully improves their motor skills may have cascading effects on self-confidence and lead to more positive social and academic outcomes.

Automaticity

Especially relevant to the concept of experiential canalization (the idea of one pathway being promoted over others through frequent use) is the idea of practice where children learn best what they practice most. When a skill or behavior is practiced repeatedly, it becomes *automated*, which means it can be done automatically, or without a lot of cognitive resources (Floyer-Lea & Matthews, 2004). Having lower-level routines, facts, and symbols automated enables a child to then focus their attention on more complex concepts including combinations of multiple routines, facts, and symbols (Case, 1996). According to automaticity theory, EF facilitates the automation of the skills that *can* be automated and also helps in accessing and working with the stored relevant general knowledge to help in problem-solving.

There is some evidence that in early childhood, EF is important not just for academic learning but for motor tasks. In other words, EF is needed to learn the fundamental motor routines of the early childhood classroom, which then frees up cognitive resources for more complex tasks. Although positively related, EF and visuo-motor integration are not the same (Becker et al., 2014; Cameron et al., 2015; Cameron et al., 2012; MacDonald et al., 2016). For example, in one study of preschool children, aspects of EF (working memory and inhibitory control) were correlated r = .24 and .43 with visuo-motor integration after controlling for child age (Cameron et al., 2015). And another study found that after controlling for the influence of demographic variables such as gender, age, maternal education, and English Language Learner (ELL) status, EF was moderately but not substantially related to visuo-motor integration with estimates ranging from .14 to .28 in preschool and kindergarten children (Becker et al., 2014).

Although separable constructs, children may be relatively strong in EF or visuo-motor integration skills with this relative strength in one area bolstering the process of automaticity. Cameron et al. (2015) found that preschoolers with either strong inhibitory control or visuo-motor integration learned as much in print knowledge as peers who were strong in both. This study suggests a compensatory pattern where 4.5-year-olds who lack an EF component like inhibitory control may rely on visuo-motor integration skills, and vice versa. Furthermore, EF appears important for relatively younger (4-year-old) children's visuo-motor integration competence, but among 5-year-olds, EF did not predict visuo-motor integration (Becker et al., 2014). So, how EF and visuo-motor integration are associated may change during the school transition period, illustrating the bidirectional nature of skill development and the dynamic aspect of experiential canalization.

Reciprocity

Reciprocity refers to co-development, where one skill develops alongside another, and skill gains in one area track with skill gains in another. Scholars have recently highlighted the notion of bidirectional or reciprocal development among foundational cognitive skills and traditional academic domains (Fuhs et al., 2014; Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017). Reciprocity seems especially applicable to how EF and mathematics learning unfolds (Blair & Raver, 2015; Clements, Sarama, & Germeroth, 2016; Fuhs et al., 2014). For example, learning mathematics also exercises EF components such as attention, inhibitory control, and especially, working memory (Blair & Raver, 2015; Blair et al., 2015). Consistent with this notion, Kim et al. (2017) found that children's early mathematics skills contributed to the development of the EF component of attention among 5-year-olds (kindergarteners), as well as to the development of visuo-motor integration.

In another study, growth curve analyses showed that children's growth in EF and math were related between preschool and kindergarten. The study also found evidence for bidirectional relations between EF and math over preschool, but only EF predicted math in kindergarten (Schmitt et al., 2017). Similarly, Fuhs et al., (2014) found that EF and math were reciprocally related in preschool but associations changed as children entered kindergarten: EF continued to predict math but math did not predict EF between the end of preschool and the end of kindergarten. Taken together, this suggests co-development among EF, motor skills, and mathematics early on, with patterns becoming more specific over time.

Summary

Together, dynamic systems theoretical perspectives advance the view that development is multilevel, interactive, and bidirectional where children's development occurs through active exploration of the environment and dynamic interactions between child characteristics and contextual influences (McClelland et al., 2015). These theories help describe the processes, such as automaticity and reciprocity, through which these interactions occur. Moreover, these perspectives can be used to predict how children's EF and motor skills provide children with the experiences necessary to acquire the academic skills needed for early school success and how that process can reciprocally strengthen EF and motor skill development (Blair & Raver, 2015; McClelland et al., 2015). Based on research supporting the experiential and probabilistic nature of EF and motor skills, they may be fruitful targets of intervention especially in the early years (Blair & Raver, 2012; McClelland et al., 2015). Before interventions can be developed, however, there needs to be reliable and valid measures of these skills.

Measurement

A recent challenge in capturing the complexity of children's EF, motor skills, and early academic skill development is finding measures that effectively assess the constructs of interest. Another challenge is that both EF and motor skills usually are measured as separate constructs even though they likely co-develop and reciprocally influence each other (Becker et al., 2014; Cameron et al., 2015). For example, many measures of EF may also involve aspects of motor skills and vice versa, which is an example of task impurity (e.g., Best & Miller, 2010). And there is also overlap between EF, motor skills and children's early academic skills (e.g., Schmitt et al., 2017), which supports the notion that these skills develop reciprocally in early childhood. While theoretically robust, co-development in processes like EF and motor skills can thus present significant challenges to measurement. We see two sides to this issue: on the one hand, measuring skills separately improves specificity of measurement and increases validity; on the other hand, there are benefits to single measures that capture a broader set of skills and which include multiple constructs.

Advances in Direct Measures of EF and Motor Skills

Measurement work predominately focuses on EF and motor skills as separate constructs so we review measurement issues for EF and motor skills separately. Although there remains much work to be done, this research is important because it has helped clarify the aspects of EF and motor skills that are being assessed, which makes it easier to connect them to key outcomes of interest, such as school success.

Measuring EF. In addition to the rather thorny conceptual and definitional issues that have plagued the field of EF, how one measures these skills in young children at a time of rapid change has been of central concern. Partly in response to calls for tools in early childhood that are practical, feasible and ecologically-valid (e.g., McClelland & Cameron, 2012), researchers have moved away from measures that are administered in the laboratory to ones that can be used in real-world settings. Assessing children in naturalistic settings such as schools is important because children's EF helps lay the foundation for learning, and assessing EF in school can help identify children at risk (Blair, 2002). Many measures, however, require specialized materials such as computers or tablets and/or substantial time to administer (Hughes, 1998). In addition, existing measures often require children to respond with fine motor actions such as a key press on a laptop (Zelazo et al., 2013). Recent advances in measurement assess EF with multiple tasks and developing measures that are short, feasible and highly scalable. Three such measures include the EF Battery (Willoughby, Blair, Wirth, & Greenberg, 2010, 2012; Willoughby, Wirth, & Blair, 2012), the NIH Cognition Toolbox (Zelazo et al., 2013), and the Head-Toes-Knees-Shoulders (HTKS) measure of self-regulation and EF (Cameron Ponitz, McClelland, Matthews, & Morrison, 2009; McClelland et al., 2014).

Measuring motor skills. Measures of children's motor skills have been well-established for decades because of their incorporation in visuo-spatial measures of established cognitive batteries such as the Wechsler Preschool and Primary Scale of Intelligence (WPPSI™ - IV)(Wechsler, 2012), the Woodcock-Johnson Tests of Cognitive Abilities (Schrank, McGrew, & Mather, 2014), or the Stanford-Binet Tests of Intelligence (Roid, 2005). More challenging is disentangling which aspects of common motor skills measures are responsible for the now extensively documented links to academic skills (Burton & Rodgerson, 2001; Cameron et al., 2016). Several studies including the nationally-representative analyses that link children's kindergarten-entry motor skills to later elementary academic achievement used a composite measure of multiple tasks, such as building with blocks, copying designs, or drawing a person (Cameron et al., 2012; Grissmer et al., 2010; Son & Meisels, 2006).

As mentioned above, subsequent efforts to understand what aspects of motor skills drive connections to achievement have focused on visuo-motor integration, or copying a design using pencil and paper. One cross-sectional study showed that fine manual control and visual processing, which together underlie visuo-motor integration, are responsible for the links between general motor and cognitive tasks in children ages 4 to 11 (Davis, Pitchford, & Limback, 2011). The Beery VMI is arguably the best-known measure of visuo-motor integration, which includes the eponymous subtest requiring children to copy increasingly complex designs. However, Kim and Cameron (2016) reported that early motor coordination measured with a basic tracing task provided kindergarten-age children with the foundation for the more advanced skill of visuo-motor integration, which in turn, predicted their mathematics achievement.

Advances in Caregiver Ratings of EF and Motor Skills

Teacher and parent ratings of EF and motor skills can be used to capture a broad set of skills that are observed in real-world settings. In addition, caregiver ratings are often a more efficient and economical solution compared to direct assessments, although they also have drawbacks. For example, in one study, teacher ratings of children's early math and language and literacy showed substantial assessor variance—also known as rater bias—compared to directly administered measures (Waterman, McDermott, Fantuzzo, & Gadsden, 2012). Despite this, other studies using teacher and parent ratings of EF and motor skills have suggested that they can be strong predictors of child outcomes. Teacher ratings of self-regulation and social-emotional skills in kindergarten were strong predictors of students' sixth grade reading and math skills after controlling for child characteristics such as IQ (McClelland, Acock, & Morrison, 2006). Another study found that parents who rated their children as having high attention and persistence (aspects of EF) at age four had nearly 50% greater odds of completing college by the time they were 25 after controlling for reading and math skills at multiple time points (McClelland et al., 2013). A recent meta-analysis also found that there were no significant differences between teacher ratings of children's inhibitory control (a component of EF) and direct assessments of inhibitory control in the associations to academic outcomes (Allan, Hume, Allan, Farrington, & Lonigan, 2014). However, the meta-analysis also found that direct assessments or teacher reports were better than using parent reports in predicting academic outcomes (Allan et al., 2014).

Similarly, a teacher-report measure called the Motor Skills Rating Scale (MSRS) was developed to measure fine motor skills, body awareness, and visuo-motor precision in K-Grade 2 (Cameron et al., 2012). The MSRS is positively related to direct assessments of corresponding skills as well as academic achievement, and can be used to assess children's motor skills in broader contexts such as classroom settings (Kim et al., 2015).

Summary of Measurement Issues

Overall, recent research on measures of EF and motor skills has focused on increasing the specificity in measurement while also assessing skills in real-world environments (McClelland & Cameron, 2012). As noted above, one challenge is that these measures likely also assess other skills. For example, the HTKS task (McClelland et al., 2014) taps aspects of EF and also includes gross motor movements. Similarly, many measures such as the EF battery (Willoughby, Blair, et al., 2012) and the NIH Toolbox (Zelazo et al., 2013) require children to respond with fine motor actions such as a key press on a laptop. In terms of motor skills measures, many of them require children to focus, pay attention and remember the instructions to successfully complete the task, all which are aspects of EF. Thus, it is possible that these demand characteristics of measures can contribute to task impurity between EF and motor skills assessments. However, they are also examples of how these skills likely co-develop in young children and can be used to assess both EF and motor skills together. Work on caregiver ratings and direct assessments of children's EF and motor skills demonstrates that measures can provide complementary information related to specificity and the interrelated nature of skills in young children. Although challenges remain, both types of assessments demonstrate meaningful predictive associations with children's outcomes in the short- and long-term.

Interventions: Implications for Education

Intervention research in early childhood examines how to strengthen foundational learning skills such as EF and motor skills in part because of the rapid cognitive and brain development that occurs early in life, which also results in considerable malleability. Much of this work aligns with the theoretical conceptualizations mentioned above showing that children's development in different domains demonstrates relative plasticity over time and is the result of dynamic and bidirectional relations that occur at multiple levels of influence (Blair & Raver, 2015; McClelland et al., 2015).

Interventions to Improve EF and School Readiness

Significant progress has been made in recent years on efforts to improve EF and school readiness in young children (Bierman et al., 2014; Blair & Raver, 2014; Schmitt, McClelland, Tominey, & Acock, 2015). These efforts have largely involved classroom educational programs or direct training of EF (e.g., working memory training programs). We highlight the educational programs in classroom settings because of our interest in programs that are ecologically valid and show the potential to transfer to children's skills in their everyday lives (although see Zelazo et al., 2016 for information about other types of interventions). In general, results from studies utilizing randomized control trial (RCT) designs suggest that educational programs that try to build EF skills have been directly and indirectly related to improved EF and academic outcomes in young children, although results vary based on factors such as age, gender, and demographic risk (Bierman et al., 2014; Blair & Raver, 2014; McClelland, Tominey, Schmitt, & Duncan, 2017; Schmitt et al., 2015).

For example, children who participated in the Head Start REDI intervention, which promotes social-emotional, language, and literacy skills, improved their social-emotional skills, EF, and academic outcomes in preschool and a year later after they transitioned into kindergarten (*d* = .13 - .40). Effects were strongest for children from disadvantaged families and some effects strengthened over time (Bierman, Nix, Greenberg, Blair, & Domitrovich, 2008; Bierman et al., 2014).

There is also evidence that programs that explicitly focus on a specific domain such as EF or academic skills can show effects in other areas. For example, an intervention consisting of EF games played during Circle Time in preschool (called Red Light, Purple Light Circle Time Games; McClelland & Tominey, 2015; Schmitt et al., 2015; Tominey & McClelland, 2011) improves children's EF and reading and math skills in two RCTs (*d* = .16 - .32). Effects on improvements in math were strongest for children who were ELLs and from low-income families (*d* = .44) (Schmitt et al., 2015). Other research has shown that the Boston Public School Prekindergarten program, which focused primarily on language and math, showed significant improvements in math and reading (*d* = .44 - .62). Children in high-poverty schools also showed significant improvements in EF (*d* = .33) supporting bidirectional relations between EF and academic achievement (Weiland & Yoshikawa, 2013).

Taken together, research indicates that interventions to improve EF and school readiness can be effective with variation in effects seen for different groups of children and depending on the fidelity of implementation. More research is needed to improve our understanding of long-term effects, cost-benefits of different programs and how programs may work differently for different children (McClelland et al., 2017). One summary of effective interventions among children ages 4 to 12 found that incorporating movement, repeated practice, and increasing the cognitive complexity of activities maximize benefits to EF (Diamond & Lee, 2011). However, even promising interventions can be a challenge to implement successfully. For a play-based preschool program called Tools of the Mind, intervention results were mixed with some research finding small to moderate effects on improved child EF and academic outcomes overall (d = .07 - .14) and larger effects (d = .42 - .80) on outcomes for children in high-poverty schools (Blair & Raver, 2014). Another study, however, did not find any significant results of Tools of the Mind on children's EF or academic outcomes (Farran, Wilson, & Lipsey, 2013). The authors suggested that how the curriculum was implemented by teachers was important in explaining null effects. Similarly, there is contrasting evidence of causal relations between EF and academic achievement, with some meta-analyses finding evidence in support of causal links (e.g., Allan & Whitehurst, 2015) and others finding a lack of support for such a link (e.g., Jacobs & Parkinson, 2015).

Interventions to Improve Motor Skills and School Readiness

Compared to EF, there is less work that aims to explicitly improve children's motor skills, and even fewer interventions that make connections to academic skills. Existing evidence suggests that researchers should strive to improve quality and to expand intervention efforts to typically developing populations to see if approaches that are effective among children with a diagnosis generalize. For example, regarding interventions on motor skills only, a review of 11 mostly school-based interventions with children with a developmental delay showed that multiple gross motor skills, such as running, jumping, throwing, and catching, improved significantly with on average 13 weeks of intervention occurring 1-4 times per week (Kirk & Rhodes, 2011). Among typically-developing children, strong motor skills signal better school readiness in multiple areas, suggesting that intervening with children whose motor skills are weak may smooth their transition to school (Pagani & Messier, 2012). In one study of school readiness among 522 children living in a poor urban area, those with better gross motor skills also displayed less emotional distress, more prosocial behavior, and were better able to engage in classroom activities (Pagani & Messier, 2012). That study also found that children who had good fine motor and perceptual skills had better number knowledge, less inattentive and hyperactive behaviors, and also engaged better in classroom opportunities.

Minds in Motion is one example of a successful intervention that targets children's fine and visuo-motor integration skills in another sample of low-income children in an urban area (Brock, Murrah, Cottone, Mashburn, & Grissmer, in press). The Minds in Motion curriculum, which used manipulatives and guided object play and was delivered after-school, improved a range of skills including EF and visuo-motor integration among typically developing kindergarten and 1st graders (Brock et al., in press). Guided object play is a developmentally appropriate activity that involves caregivers showing children specific ways of interacting with materials including arts-and-crafts and board games (Weisberg, Hirsh-Pasek, & Golinkoff, 2013). Further, growing evidence suggests that certain adult-guided interactions with objects are associated with gains in children's cognitive skills (such as EF and visuo-motor integration) as well as academic skills (such as mathematics) (Brock et al., in press; Cameron, in press; Levine, Ratliff, Huttenlocher, & Cannon, 2012; Siegler & Ramani, 2009).

Overall, intervention research on EF and motor skills suggests that these skills are foundational for early learning and also malleable to change during the early childhood period, which suggests possible windows of intervention. Reflecting the theoretical framework mentioned above, interventions that emphasize the bidirectional development of foundational learning skills are likely to be most effective.

Next Steps in the Study of Early Skill Co-Development

This review has focused on two skills (EF and motor skills) as being foundational for children's early learning and school readiness. Our goal is not to focus on EF and motor skills at the expense of other skills but instead to use them as examples of how skills *develop together* in young children. Because our review is limited in what we can address, we end with a few next steps. First, although EF and motor skills are important, they are not the only factors and it is important to also consider other key domains such as early language and vocabulary development (Slot & von Suchodoletz, 2018). Thus, moving forward, research needs to focus on a variety of key domains of development and how they develop together rather than pitting one set of skills against another.

Second, continuing to ask questions such as "How can we best measure these skills?" and "What measure or measures are most appropriate for a given outcome, context, or question of interest?" are critical for moving the field forward. Research on measurement of child skills needs to focus on how to specifically measure domains of interest (e.g. EF and or motor skills), along with an appreciation for how measures often overlap in the constructs they are assessing especially in young children. The emerging domain-specific associations among EF or motor skills components and specific aspects of literacy or mathematics calls for mapping at a more fine-grained level (Kim & Cameron, 2016). Understanding which component of EF, such as inhibitory control, is most strongly associated with a particular mathematics skill, such as quantitative comparisons, at particular times of the school transition can lead to more targeted supports.

Researchers can continue thinking carefully about how to best intervene to support children's school readiness and overall development. Interventions to support EF and motor skills have demonstrated effectiveness in randomized control trials, but not all studies find positive effects. One way to resolve this issue is to look at differential treatment effects for different groups of children. It is likely that one size does not fill all children in terms of interventions (McClelland et al., 2017). Future research needs to include evidence from recent randomized controlled trials (e.g., Schmitt et al., 2015; Blair & Raver, 2014) along with long-term effects of interventions to further investigate these issues (Sasser, Bierman, Heinrichs, & Nix, 2017). In addition, researchers have called for strengthening the analytic toolbox in terms of the metrics used to evaluate intervention effectiveness. For example, Greenberg and colleagues have advocated for metrics such as relative risk reduction that are commonly used in public health and medical studies to be more widely used in developmental and education research (Greenberg & Abenavoli, 2017). Such metrics have advantages of giving additional and potentially more meaningful ways to assess program impact than traditional metrics such as effect sizes. Finally, schools and early childhood programs need practical and feasible activities that can be easily integrated into teacher's curriculum and that are highly scalable. These may have the best chance of uptake by practitioners and teachers.

Conclusion

Children enter formal schooling contexts with a portrait of different skills that co-develop throughout the early childhood years. Children's EF and motor skills are foundational skills that allow children to successfully navigate social and school settings. EF enables children to focus, remember, and process information and are significantly predictive of short- and long-term indicators of success (McClelland et al., 2013; Moffitt et al., 2011). Motor skills help children recognize and manipulate many of the symbolic forms that are the vehicle for school academic domains (Cameron et al., 2016). Theoretical perspectives that emphasize the bidirectional and reciprocal development of these skills provide a crucial lens through which researchers can better understand how these processes unfold in young children. Advances in the measurement of EF and motor skills have improved the reliability and validity and clarity of what is being assessed.

This is important because it makes it easier to examine how these skills are related to outcomes of interest such as school success. Intervention research provides evidence that support the malleability of these skills and also provides insight to researchers, policy-makers and practitioners about how to best promote these skills in young children. We end with a few concluding comments that can be used to guide future work.

First, both EF and motor skills help children transition to school (Cameron et al., 2012; McClelland et al., 2014; Pagani & Messier, 2012). EF involves multiple components which are used separately and together in many classroom tasks and academic learning (Blair & Raver, 2015; McClelland et al., 2015). Second, the evidence is strongest for the visuo-motor integration aspect of fine motor skills—it predicts both literacy outcomes and mathematics (Cameron et al., 2016). Third, EF and motor skills develop together, a relative strength in one may make up for a weakness in the other (Cameron et al., 2015), and the association between the two skills appears stronger among younger children (Becker et al., 2014). Fourth, assessing EF among young children is challenging but progress is evident; assessors and researchers need to decide if they want an overall assessment or to focus on individual components (McClelland et al., 2014; Zelazo et al., 2013; Zelazo et al., 2016). Both direct assessments and observer ratings (especially teacher ratings) of children's skills have the potential provide information that can be used to support children during the transition to school. Finally, interventions can be effective although more work is clearly needed to understand the conditions where interventions would have the most success with a given group of children. Overall, EF and motor skills are foundational learning skills that develop together as children move through the early childhood years and can be fruitful targets for promoting school readiness across cognitive and academic domains.

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