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Review

Learning executive function and early mathematics: Directions of causal relations

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ABSTRACT

Although there has been much recent attention to young children's development of executive function and early mathematics, few studies have integrated the two. Here we review the evidence regarding executive function and mathematic achievement in the early years. After defining the executive function processes we consider, we briefly address the question of whether executive function can be taught in schools. We then turn to the relations between executive function and achievement. We begin with a review of the larger literature on correlations between the two, both concurrent and predictive. This leads to the fewer but more directly educationally-relevant causal studies. We conclude that developing both executive function processes and mathematical proficiencies is essential for young children and suggest that high-quality mathematics education may have the dual benefit of teaching this important content area and developing executive function processes.

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1. Introduction

To learn and to solve problems, people need resources. One type of resource allows them to control, supervise, or regulate their own thinking, and behavior. Such *executive function* (EF) processes develop most rapidly in the early childhood years. Others are domain-specific resources, such as mathematics proficiencies (National Research Council, 2001). In this paper, we address the interrelations of these two as they contribute to young children's learning and development in mathematics. We begin with brief illustrations of why each is important.

Cognitive processes such as EF appear prima facie to be connected to students' achievement in school. Children need to plan ahead, focus attention, and remember past experiences. According to some, EF processes constitute "a major characteristic of productive mathematics learning" (De Corte, Mason, Depaepe, & Verschaffel, 2011, p. 155). Such EF processes support children's learning across subject matter areas, but may be particularly important to mathematics. As one example, when the initial reading of an arithmetic problem is not the correct one, children need to *inhibit* the first impulse to answer (incorrectly) and carefully examine the problem. Consider the following problem, "There were six birds in a tree. Three birds already flew away. How many birds were there from the start?" Children have to inhibit the immediate desire to subtract engendered by the phrase "flew away" and instead calculate the sum (through addition, counting on, other other strategies). Over the last 100 years, the demand for the application of such EF processes as inhibition has increased in mathematics education (Baker et al., 2010). Together, these processes allow children to complete tasks even when facing difficulties in problem solving and/or learning, fatigue, distraction, or decreased motivation (Blair & Razza, 2007; Neuenschwander, Röthlisberger, Cimeli, & Roebers, 2012). It is thus unsurprising that Kindergarten teachers say that such EF processes (albeit not by that name) are as important as academics (Bassok, Latham, & Rorem, 2016). Most teachers rate EF components such as inhibition and attention shifting, as important for math thinking and learning, and these ratings increase with teaching experience (Gilmore & Cragg, 2014). Thus, on argument is that EF development is a prerequisite for learning mathematics.

Of course, domain-specific resources, such as mathematical proficiencies, must be developed for children to progress in acquiring mathematical knowledge and problem-solving competencies (Passolunghi & Lanfranchi, 2012; Sarama & Clements, 2009). Mathematics proficiencies include five intertwined strands: conceptual understanding, procedural fluency, strategic competence, adaptive reasoning (capacity for logical thought, reflection, explanation, and justification), and productive disposition (National Research Council, 2001). Early mathematical proficiency has been identified as the best predictor of later knowledge of mathematics achievement (Koponen, Salmi, Eklund, & Aro, 2013; Passolunghi, Vercelloni, & Schadee, 2007). The mathematics that children know when they enter kindergarten and first grade predicts their mathematics achievement for years to come and throughout their school career (National Mathematics Advisory Panel, 2008). What they know in math even predicts their reading achievement—better than early literacy skills (Duncan et al., 2007; Duncan & Magnuson, 2011; Koponen et al., 2013). Mathematics, including the strands of strategic competence and adaptive reasoning (Nunes, Bryant, Barros, & Sylva, 2012; Piaget, 1970), appears to be a core component of cognition (Clements & Sarama, 2011). This suggests that high-quality mathematics education experiences may simultaneously develop mathematical proficiencies and at least some EF processes.

In this paper, we examine the literature on the directionality of the relation between EF and math to better understand how the development of both proficiencies may be supported. First, we briefly examine EF, defining EF processes and addressing the question of whether EF can be taught so as to ascertain the malleability of EF (which is critical to our questions of trainability and directionality of any effects of training). The next two sections turn to relations between executive function and achievement, reviewing correlational and causal studies, respectively. We address several questions. Are EF and achievement reliably related? Is EF a prerequisite to learning mathematics and thus must be developed or taught first? Or, does thinking and learning about mathematics help develop EF? Finally, we conclude that developing both executive function processes and mathematical proficiencies is essential for young children and suggest that high-quality mathematics education may have the dual benefit of teaching this important content area and developing EF processes.

Because we were interested in a conceptual analysis of these domains, we conducted a narrative review with systematic search procedures (see the online Supplement for detailed information). This review differs from and extends previous discussions (Bull & Lee, 2014; De Corte et al., 2011) because it is (a) focused on the early years, a time the development of EF is considered rapid, critical, and foundational; and (b) focused on the *directionality* of the correlational *and* causal relations between EF and math (we also report relations involving literacy, because the comparison to math illuminates these relationships).

2. Executive function

Researchers and other educators have used the term EF to refer to the processes involved in intentionally controlling ones' impulses, attention, thinking, and behavior. Although the field lacks a common set of processes and definitions, the broad concept of EF can be viewed as a unity functionally, but has also been analyzed into several processes (Best, Miller, & Naglieri, 2011; Huizinga, Dolan, & van der Molen, 2006; Lehto, Juujarvi, Kooistra, & Pulkkinen, 2003; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000; Raver, 2013; Schoemaker, Bunte, Espy, Deković, & Matthys, 2014). Three processes are frequently distinguished.

First, *attention shifting and cognitive flexibility* involves switching a "mental set" from one aspect of a situation to another as the situation requires. A simple example in mathematics is counting by different units (e.g., feet and inches, to find a total length). Cognitive flexibility is similarly involved in avoiding "functional fixedness"; for example, the tendency to see represented objects only in terms of their canonical function. An example in mathematics of the lack of cognitive flexibility is repeating the same solution strategy even after it has failed.

Second, *inhibitory control* involves suppressing unproductive responses or strategies, such as controlling a proponent response (e.g., the first solution or answer that occurs to you, as in the "six birds in a tree" example) to think about better strategies or ideas. Ignoring visually salient extraneous information in a mathematics word problem is another example.

Third, *working memory* involves a system that is responsible for the short-term holding and processing of information. The EF process is often identified with an emphasis on *updating* working memory as new information is processed; that is, maintaining, manipulating, and adding relevant information often while engaging in another cognitively demanding task. Students solving a measurement problem may have to keep the problem situation and their solution in mind while they perform a necessary computation, interpret the result of the computation in terms of the measurement units, and then apply that to the problem context to solve the problem.

Not all studies have identified the same EF factors, for example, one validated separate latent factors for working memory and attention shifting, but no coherent latent factor for inhibition