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The Development of Academic Achievement and Cognitive Abilities: A Bidirectional Perspective

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Abstract

Developing academic skills and cognitive abilities is critical for children's development. In this article, we review evidence from recent research on the bidirectional relations between academic achievement and cognitive abilities. Our findings suggest that (a) reading/mathematics and cognitive abilities (i.e., working memory, reasoning, and executive function) predict each other in development, (b) direct academic instruction positively affects the development of reasoning, and (c) such bidirectional relations between cognitive abilities and academic achievement seem weaker among children with disadvantages (e.g., those with special needs or low socioeconomic status). Together, these findings are in line with the theory of mutualism and the transactional model. They suggest that sustained and high-quality schooling and education directly foster children's academic and cognitive development, and may indirectly affect academic and cognitive development by triggering cognitive-academic bidirectionality.

Keywords

bidirectional; mutualism; transactional; academic development; cognitive development

Academic achievement plays an important role in child development because academic skills, especially in reading and mathematics, affect many outcomes, including educational attainment, performance and income at work, physical and mental health, and longevity (Calvin et al., 2017; Kuncel & Hezlett, 2010; Wrulich et al., 2014). Not surprisingly, much research in the past several decades has explored factors associated with academic achievement and how to incorporate these factors into intervention and instruction to improve academic performance and remediate learning difficulties (for reviews, see Gersten, Fuchs, Williams, & Baker, 2001; Stockard, Wood, Coughlin, & Khoury, 2018). This rich body of research has identified two major categories of factors important for academic development: One is a set of foundational domain-specific skills. For example, meta-linguistic skills (e.g., phonological processing, orthographic knowledge, morphological

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awareness), fluency, and comprehension strategies are critical for word reading and reading comprehension (National Reading Panel, 2000), and numerical skills such as number sense and fact retrieval are often suggested as foundations for mathematics (Geary, 2004).

The other set of factors important for academic performance consists of cognitive abilities, including but not limited to working memory (simultaneous information storage and manipulation; Peng et al., 2018), reasoning (the capacity to solve novel and complex problems; Sternberg, Kaufman, & Grigorenko, 2008), and executive function (cognitive and social-emotional processes that underlie goal-directed behavior such as flexible thinking, self-control, and self-regulation; Best & Miller, 2010). In this article, we focus on the relation between academic achievement and cognitive abilities. We also consider a relatively new perspective for this relation: *mutualism* or *bidirectionality*—the facilitatory, reciprocal effects between individual skills that support and amplify the development of academic achievement and cognitive performance (van der Maas et al., 2006).

In the following sections, we first describe the conventional assumption that cognitive abilities lead to academic achievement. Next, we present theories and hypotheses suggesting that these are related bidirectionally, and we review recent research on these bidirectional effects with a focus on how cognitive abilities (working memory, reasoning, and executive function) are related to reading and mathematics achievement. We also discuss mechanisms for bidirectional relations between cognitive abilities and academic achievement, with a focus on a transactional framework in the context of education. Finally, we make recommendations for studying these bidirectional relations.

Unidirectional Effect: Cognitive Abilities → Academic Achievement

Conventional opinions and most research on the relation between cognitive abilities and academic achievement have treated cognitive abilities as foundational constructs, presupposing that cognitive abilities are primary and cause academic outcomes (e.g., Cattell, 1987; Sternberg et al., 2008). This view of *cognitive abilities* → *academic achievement* is best explained by two influential cognitive theories: investment theory and dual-process theory. According to the investment theory, the development of cognitive abilities is influenced mostly by biological, genetic, and health factors, not by education (Cattell, 1987; Deary, Penke, & Johnson, 2010). Thus, academic performance is a result of the *investment* of cognitive abilities and the environmental stimulation offered by, for example, educational settings, and cognitive abilities are assumed to be the basis for the development of academic performance (Cattell, 1987).

Similarly, the dual-process theory of higher cognition claims that individuals process familiar information in an autonomous way that requires few cognitive resources, and they process novel information in a controlled way that requires many cognitive resources (Evans & Stanovich, 2013). Thus, the involvement of cognitive abilities in an academic task is determined mostly by how efficiently the academic task can be performed, which is closely associated with long-term memory of knowledge of the task. Therefore, performing an academic task at an early stage of learning should take more effort and be more demanding cognitively, whereas with further development and accumulated knowledge,

cognitive abilities may be less involved, so individuals are more likely to rely on direct retrieval of knowledge from long-term memory.

Bidirectionality: Cognitive Abilities ↔ Academic Achievement

In recent years, the unidirectional relation between cognitive abilities and academic performance has been challenged by the theory of mutualism, which claims that different types of skills and abilities become bidirectionally related during human development as a consequence of mutually beneficial interactions between originally uncorrelated cognitive processes (van der Maas et al., 2006). Therefore, cognitive abilities and academic achievement should influence each other through development, and 1) the relation between academic achievement and relevant important cognitive abilities (working memory, reasoning, executive function) should increase with age, 2) academic achievement and these cognitive abilities should predict each other from a longitudinal perspective, and 3) interventions targeting these cognitive abilities should result in improved academic performance and vice versa. Next, we review evidence for each of these hypotheses.

Age Effect

Meta-analyses are a major source of evidence for an age effect. They include studies tapping different age groups, so they can provide a sufficiently wide age range and enough statistical power to detect whether the relation between cognitive abilities and academic performance increases with age. In a meta-analysis of 680 studies on the relations between nonverbal reasoning and reading/mathematics across a wide range of age groups (3–80 years old; Peng, Wang, Wang, & Lin, 2019), these relations increased with age, even after controlling for confounding variables (i.e., different types of reading or mathematics skills, socioeconomic status [SES], and sample types). However, the age effect was relatively small (correlations increased by about .03 for every decade). In another metaanalysis of 197 studies of typically developing individuals (4–80 years old; Peng et al., 2018), the relations between reading and working memory increased with grade level, even after controlling for confounding variables (i.e., publication type, types of tasks, working memory materials, and bilingual status). This meta-analysis also suggested that reading development might further strengthen the relations between working memory and verbal long-term memory, thus boosting verbal working memory and its role in reading development. Such bidirectional relations between reading and verbal working memory suggested that domain-specific features of working memory can be attributed in part to academic development.

Three other meta-analyses have explored the relations between executive function and academic achievement, with findings showing a less clear age effect. One meta-analysis examined the relation between executive function (including working memory, inhibition, and flexibility) and reading in individuals from age 6 years to adulthood (Follmer, 2018). The results did not indicate that this relation varied with age or age group (ages 6–11 vs. ages 12–17 vs. adult), although the relation was smaller for adults ($r = .25$) than for children and adolescents ($r_s = .33\text{--}.38$). In another meta-analysis of school-age children, the relation between executive function (including working memory, attentional control, flexibility, and inhibition) and academic achievement did not vary with age, but the authors claimed that

this relation was somewhat stronger for children and youth aged 6–18 than for children aged 3–5 (Jacob & Parkinson, 2015). Finally, two meta-analyses studied the relation between flexibility and academic performance among elementary school children (Yeniad, Malda, Mesman, van IJzendoorn, & Pieper, 2013). Their findings also did not suggest that the relation between flexibility and reading/mathematics varied with age.

Longitudinal Relations

In a recent meta-analysis (Peng et al., 2019), my colleagues and I explored bidirectional relations between cognitive abilities and academic achievement from a longitudinal perspective. The findings suggest that nonverbal reasoning and reading/mathematics predicted each other in development even after controlling for initial performance, although almost all these synthesized longitudinal relations were from studies of children (ages 6–10). Several individual studies with more complicated research designs have shown that working memory, executive function, and IQ are related longitudinally to academic achievement across childhood and early adulthood. Specifically, using cross-lagged modeling on a large data sample from the Early Childhood Longitudinal Study, Kindergarten, one study showed that working memory and reading/mathematics significantly predicted each other from the beginning of kindergarten through second grade (Miller-Cotto & Byrnes, 2019). Another study showed a bidirectional relation between executive function (including flexibility, working memory, and inhibition) and mathematics, and a significant relation between the growth of executive function and the growth of mathematics, over the pre-school period (Schmitt, Geldhof, Purpura, Duncan, & McClelland, 2017). However, this study did not show such a bidirectional relation between executive function and reading.

Other studies have examined the relation between IQ (indicated as performance IQ and full-scale IQ from the Wechsler Intelligence Scale) and reading (based on a Woodcock–Johnson reading composite) from first through 12th grades based on latent change score models (Ferrer et al., 2007; Ferrer, Shaywitz, Holahan, Marchione, & Shaywitz, 2010). They found a positive dynamic relation between reading and IQ. They also found that the dynamics of reading and IQ appeared to be of stronger magnitude from first through third grade, less strong from fourth through eighth grade, and weaker from ninth through 12th grade, and that such bidirectional effects were obvious only among typically developing children, not among children with learning disabilities. In a more recent study, latent change score models were used to demonstrate that vocabulary and nonverbal reasoning mutually influenced each other during development (Kievit, Hofman, & Nation, 2019; Kievit et al., 2017); this bidirectional effect seemed stronger among 6- to 8-year-olds than among 14- to 25-year-olds.

Intervention Effects

In comparison with correlational studies, intervention studies with rigorous designs (e.g., randomized controlled trials) can offer convincing evidence for bidirectional relations between cognitive abilities and academic achievement if such relations exist. In terms of the training effects of cognitive abilities on academic achievement, most intervention studies from the last two decades have focused on short-term intensive working memory

and executive function training. However, meta-analyses have suggested that although such cognitive training has resulted in effects on performance of trained or similar cognitive tasks, evidence of transfer effects on nontrained academic performance has been weak or rare (e.g., Jacob & Parkinson, 2015). In contrast, reviews and meta-analyses have documented positive effects of academic instruction on cognitive abilities. In one meta-analysis of 328 intervention studies of direct academic skill instruction (including reading, math, language, spelling, and multiple or other academic subjects) among school-age children, academic instruction positively affected academic performance, and those effects transferred to performance on measures of ability and IQ—although the authors did not describe these measures in detail (Stockard et al., 2018).

Mechanisms Of Cognitive-Academic Bidirectionality

Researchers have proposed several mechanisms for cognitive-academic bidirectionality. For instance, Cattell's investment theory posits that reasoning ability underlies the acquisition of academic achievement because greater reasoning facilitates the use of analogies and abstract schema that help organize and solidify academic knowledge (for an updated perspective on Cattell, see Schweizer & Koch, 2002). In contrast, concrete knowledge may benefit more abstract cognitive abilities through mechanisms such as semantic bootstrapping; according to this hypothesis, children with more advanced verbal skills (e.g., vocabulary) can decompose abstract cognitive problems into constituent rules more efficiently (e.g., Kievit et al., 2017). The availability of greater verbal resources may also lower demands on working memory for maintaining and applying such rules (Gathercole, Service, Hitch, Adams, & Martin, 1999).

Transactional processes are another potentially important mechanism (Dickens & Flynn, 2001; Tucker-Drob, Briley, & Harden, 2013); researchers claim that genetic influences on cognition increase from infancy to adulthood and are maximized in more advantaged socioeconomic contexts. The net result is the mutual influence between academic achievement and cognitive abilities, which is moderated largely by the environment, so this mutual influence is more likely to occur in relatively richer as opposed to lower-income environments (Tucker-Drob et al., 2013). Two related but relatively independent environmental factors are often considered: schooling and learning experiences or opportunities associated with families' SES (Armor, Marks, & Malatinszky, 2018).

Schooling, with its primary function of academic instruction, can explain bidirectional relations between cognitive abilities and academic performance (Ceci & Williams, 1997; Jacob & Parkinson, 2015; Ritchie & Tucker-Drob, 2018). Early on, children use cognitive abilities to learn academic skills, and performing most academic tasks involves the use of those cognitive abilities (Evans & Stanovich, 2013; Peng et al., 2018). Thus, academic tasks practiced during schooling may offer long-term training for cognitive abilities, too. Following this logic, the bidirectional relations between cognitive abilities and reading/mathematics may be most obvious during elementary and secondary schooling, when reading and mathematics are taught systematically and practiced intensively (Peng et al., 2019). Indeed, this hypothesis can help explain why bidirectional relations between academic achievement and reasoning found in longitudinal data are stronger among

children than among adolescents and adults (Ferrer et al., 2007, 2010; Kievit et al., 2019). In addition, schooling may promote teacher–student interactions that directly improve executive function among young children (Vandenbroucke, Spilt, Verschueren, Piccinin, & Baeyens, 2018), which may indirectly contribute to cognitive-academic bidirectionality (e.g., schooling → teacher-student interactions → executive function → academic achievement).

Learning experiences or opportunities associated with SES also influence bidirectional relations between cognitive abilities and academic performance. In high-SES contexts, children have abundant opportunities for positive learning experiences, whereas opportunities are much fewer in low-SES contexts (Duncan & Murnane, 2011). Much research has documented the effectiveness of early academic intervention on academic performance among children from low-SES backgrounds or with special needs (Dietrichson, Bøgg, Filges, & Klint Jørgensen, 2017; Jacob & Parkinson, 2015). However, the effects of such early academic intervention generally fade after the intervention (Jenkins et al., 2018), and fadeout is more likely among those who had very low academic skills before treatment (Bailey et al., 2016). These findings, together with the null findings obtained in longitudinal data for bidirectional relations between cognitive skills and academic performance among children with learning disabilities (Ferrer et al., 2010), further support the transactional model. That is, children with advantages (e.g., with high SES and relatively strong cognitive abilities and foundational academic skills) in early development are more likely to trigger and benefit from cognitive-academic bidirectionality. That said, researchers have also suggested that sustained high-quality schooling may offset the negative effects of low SES on academic achievement (Jenkins et al., 2018) and decrease the inhibitive effects of low SES on relations between cognitive abilities and academic achievement (Peng et al., 2019).

Together within the transactional model, these points have important implications for education and cognitive training. Sustained, high-quality schooling and education, especially in the primary and secondary years, not only foster children's academic and cognitive development directly but also contribute indirectly to academic and cognitive development by facilitating cognitive-academic bidirectionality. Such facilitation is especially important for children with disadvantages, who often lack the resources or foundational skills to trigger and benefit from the interaction between cognitive skills and academic performance. But the relations between reading/mathematics and cognitive abilities (working memory, reasoning, and executive function) are moderate ($r_s = .30\sim.45$, 10 ~ 20% variance overlap; Jacob & Parkinson, 2015; Peng et al., 2019), and the effect of age on these relations is small though significant (Peng et al., 2018, 2019). Thus, short-term cognitive training may be insufficient to improve academic performance. For most children, long-lasting learning or the continued experiences of using reading and mathematics skills at school may be the ideal approach to improving both cognitive abilities and academic skills (Ceci & Williams, 1997).

Conclusions And Recommendations For Further Study

Meta-analyses have provided evidence that the relations between reading/mathematics and working memory/reasoning increase with age, but age effects were unclear for relations involving executive functions. Reading/mathematics and cognitive abilities (working memory, reasoning, and executive function) predicted each other's development.

Intensive short-term cognitive training did not produce reliable transfer effects on academic achievement, but direct academic instruction positively affected cognitive development. Cognitive-academic bidirectional relations seemed weaker among children with disadvantages. Together, these findings suggest a pattern of bidirectional relations between cognitive abilities and academic achievement. However, several issues need further investigation to understand these relationships more thoroughly.

Age effects may be quite nuanced. Specifically, effects of age were not consistently reported across studies, and to the extent that evidence in favor of age-related differences in correlations have been shown, they are based mostly on meta-analyses rather than on single large-scale cross-sectional empirical studies (although see Hofman et al., 2018). Evidence from large cross-sectional studies would circumvent the potential limit of heterogeneity of methods and measures that could affect findings from meta-analyses and reviews. We need such studies, as well as large longitudinal studies (Molenaar, 2004), to investigate whether age is indeed associated with changes in the association between cognitive abilities and academic achievement. However, although the relation between cognitive abilities and academic achievement *may* vary with age, this does not necessarily indicate a causal, bidirectional relation. A range of factors—including but not limited to different age-related trajectories, changes in task demands and strategies, correlated and uncorrelated changes beyond the modeled effects, the magnitude of autoregressive paths, and time-varying disturbances—all can, and do, affect cross-sectional and longitudinal correlations so they can increase, decrease, or remain static depending on the precise causal mechanisms at play.

We also need to consider measurement issues in explaining bidirectional relations between cognitive abilities and academic achievement. First, measures of cognitive abilities and academic achievement do not necessarily reflect two discrete entities. Measures of cognitive ability often tap aspects of achievement skills (e.g., measures of verbal and numerical working memory often heavily tap knowledge of language, reading, and numerals, especially for young children), and achievement tests often measure aspects of cognitive abilities (e.g., phonological awareness and reading comprehension often tap working memory, reasoning, and executive function). In this regard, pure measures of cognitive abilities or academic achievement do not exist. In other words, part of the associations in the studies reviewed here may be explained by the inherent degree to which purportedly task-pure measurements tap many different academic and cognitive domains.

In addition, this issue may be especially pressing when considering executive function (Jacob & Parkinson, 2015; Miyake & Friedman, 2012). Different executive functions are often entangled, and it is difficult to establish that different executive tests assess different components of executive function (Miyake & Friedman, 2012). Moreover, executive function is a complex and developmentally changing construct (Best & Miller, 2010). Different executive functions have different developmental trajectories. Among all executive functions, inhibition seems to develop first and mature in early childhood, whereas flexibility develops along a slower, longer trajectory until late adolescence (Best & Miller, 2010; Zelazo & Carlson, 2012). Executive functions that do not include motivation and emotion processing tend to mature faster than executive functions that do (e.g., self-regulation and control; Zelazo & Carlson, 2012). Thus, researchers may be able to

more thoroughly explain and further investigate inconclusive effects of age on the relation between executive functions and academic performance by considering the measurement and development of executive function.

We should also consider moderators on the bidirectional relations. Studies (Ferrer et al., 2007, 2010) show that although IQ is related bidirectionally to reading during development, IQ seems to drive this relation, partly in line with investment theory (academic skills develop through the investment of cognitive abilities). Similarly, although another study (Schmitt et al., 2017) showed a bidirectional relation between mathematics and executive function during the preschool years, it also found that, starting in kindergarten, only executive function predicted mathematics performance. Moreover, evidence from longitudinal studies suggests that bidirectionality may exist within an academic domain (e.g., different types of mathematics promote each other's development; Hofman et al., 2018), across academic domains (e.g., reading and mathematics mutually promote each other's development; Schmitt et al., 2017), and between academic and social-emotional domains (e.g., bidirectional relations between self-concept/motivation and academic performance; Sewasew & Schroeders, 2019). These findings suggest that the directionality of the relation between cognitive abilities and academic achievement, and the magnitude of this directionality may be further explained and moderated by developmental stages, domains of academic skills, types of cognitive skills, and academically relevant social-emotional factors.

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