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

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Abstract

The development of academic achievement and cognitive abilities is critical for child 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 working memory/reasoning/executive function predict each other in development; (b) direct academic instruction exerts positive effects on reasoning development; and (c) such cognitive-academic bidirectional relations seem weaker among children with disadvantages (e.g., 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/education directly fosters children's academic and cognitive development, and may have indirect effects on academic and cognitive development by triggering cognitive-academic bidirectionality.

Keywords: Bidirectional, Mutualism, Transactional, Academic Development, Cognitive Development

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

Academic achievement plays an important role in child development, because academic skills, especially in reading and mathematics, affect many lifespan outcomes including educational attainment, performance/income at work, physical/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 important factors associated with academic achievement and how to incorporate these factors into intervention/instruction to facilitate 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, and morphological 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/social-emotional processes that underlie goal-directed behavior such as flexible thinking, self-control, and self-regulation; Best & Miller, 2010). In the present study, we focus on the relation between academic achievement and cognitive abilities and provide a review on 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 theory and hypotheses suggesting that these are bidirectionally related, and we review recent research on these bidirectional effects, with a focus on the relations between working memory/reasoning/executive function and reading/mathematics achievement. We further discuss mechanisms for cognitive-academic bidirectional relations, with a focus on a transactional framework in the context of education. Finally, we make recommendations for future studies on bidirectional relations between cognitive abilities and academic achievement.

Unidirectional Effect: Cognitive Abilities → Academic Achievement

Conventional opinions and a majority of research on the relation between cognitive abilities and academic achievement have treated cognitive abilities as foundational constructs, presupposing that cognitive abilities are primary, causative of academic outcomes (e.g., Cattell, 1987; Sternberg et al., 2008). This view of *cognitive abilities* → *academic achievement* is best explained within two influential cognitive theories: investment theory and dual-process theory. According to investment theory, the development of cognitive abilities is influenced mostly by biological/genetic/health factors, not by education (Cattell, 1987; Deary, Penke, & Johnson, 2010). Academic performance is thus 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, yet 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 mostly determined by how efficiently the academic task can be performed, which is closely associated with long-term memory of knowledge for the task. It should therefore be more effortful and cognitively demanding to perform an academic task at an early stage of learning, whereas with further development/knowledge accumulation, cognitive abilities may be less involved in performing this particular academic task; individuals will then be more likely to rely on direct retrieval of knowledge from long-term memory for academic task performance.

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/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). Cognitive abilities and academic achievement should therefore influence each other through development, and (a) the relation between academic achievement and relevant important cognitive abilities (working memory/reasoning/executive function) should increase with age, (b) academic achievement and these cognitive abilities should predict each other from a longitudinal perspective, and (c) interventions targeting these cognitive abilities should result in improvement of academic performance and vice versa. Here, we review evidence for each of these hypotheses.

Age effect. One big source of evidence for an effect of age comes from meta-analyses, in which studies tapping different age groups 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 non-verbal reasoning and reading/mathematics across a wide range of age groups (3~80 years old), Peng, Wang, Wang, and Lin (2019) found that these relations increased with age, even after controlling for confounding variables (i.e., different types of reading/mathematics skills, socioeconomic status [SES], and sample types). However, this age effect was relatively small (correlations increased by about .03 for every decade). In another meta-analysis of 197 studies of typically developing individuals from 4 to 80 years old, Peng et al. (2018) found that 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 strengthening 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. Specifically, Follmer (2018) conducted a meta-analysis of the relation between executive function (including working memory, inhibition, and flexibility) and reading in a sample from 6 years of age to adulthood. The results did not indicate that this relation varied with age or age group (age 6–11 vs. age 12–17 vs. adult), although the relation was smaller for adults (r = .25) than for children/adolescents (rs = .33~.38). In another review/meta-analysis based on school-age children, Jacob and Parkinson (2015) reported that 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 age 6–18 than for age 3–5. Yeniad, Malda, Mesman, van IJzendoorn, and Pieper (2013) conducted two meta-analyses to study the relation between flexibility and academic performance among elementary school children. 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) explored bidirectional relations between cognitive abilities and academic achievement from a longitudinal perspective. Their findings suggested that nonverbal reasoning and reading/mathematics predicted each other in development even after controlling for initial performance, although almost all of these synthesized longitudinal relations were from studies of children (age 6–10). Several individual studies with more complicated research designs have detected longitudinal relations between working memory/executive function/IQ and academic achievement across childhood and early adulthood.

Specifically, using cross-lagged modelling on a large data sample from the Early Childhood Longitudinal Study, Kindergarten (ECLS-K), Miller-Cotto and Byrnes (2019) found that working memory and reading/mathematics significantly predicted each other from the beginning of kindergarten through second grade. Schmitt, Geldhof, Purpura, Duncan, and McClelland (2017) found 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 preschool period. However, Schmitt et al. did not find such a bidirectional relation between executive function and reading.

Ferrer and colleagues (Ferrer et al., 2007; Ferrer, Shaywitz, Holahan, Marchione, & Shaywitz, 2010) studied the relation between IQ (indicated as performance IQ and full scale IQ from the Wechsler Intelligence Scale) and reading (Woodcock-Johnson reading composite) from 1st through 12th grade based on latent change score models. They found that (a) there was a positive dynamic relation between reading and IQ; (b) the dynamics of reading and IQ appeared to be of stronger magnitude from 1st through 3rd grade, less strong from 4th through 8th grade, and weaker from 9th through 12th grade; and (c) such bidirectional effect was obvious only among typically developing children, not among children with learning disabilities. More recently, Kievit et al. (2017, 2019) used latent change score models to demonstrate that vocabulary and nonverbal reasoning mutually influenced each other during development; this bidirectional effect seemed stronger among children (age 6–8) than among adolescents/adults (age 14–25).

Intervention effects. In comparison with correlational studies, intervention studies with rigorous designs (e.g., randomized controlled trials) can offer most convincing evidence for bidirectional relations between cognitive abilities and academic achievement if they exist. Regarding training effects of cognitive abilities on academic achievement, the majority of the literature on intervention studies from last two decades or so has focused on short-term intensive working memory/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, there has been very weak or little evidence of transfer effects on nontrained academic performance (e.g., Jacob & Parkinson, 2015). In contrast, reviews and meta-analyses have documented positive effects of academic instruction on cognitive abilities. In a compelling meta-analysis, Stockard et al. (2018) reviewed 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 had positive effects on academic performance, and those effects transferred to performance on ability/IQ measures—although the authors did not describe the ability/IQ measures in detail.

Mechanisms of Cognitive-Academic Bidirectionality

Researchers have proposed several mechanisms for cognitive-academic bidirectionality. For instance, Cattell’s investment theory posits that it is the reasoning ability that underlies the acquisition of academic achievement, as greater reasoning facilitates the employment 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’ – This hypothesis would entail that children with better verbal skills (e.g., vocabulary) are more able to efficiently decompose abstract cognitive problems into constituent “rules” (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). Another potentially important mechanism is the transactional process highlighted by Dickens and Flynn (2001) and Tucker-Drob, Briley, and Harden (2013). The transactional model claims that genetic influences on cognition increase from infancy to adulthood and are maximized in more advantaged socioeconomic contexts. The net result of this transactional process is the mutual influence between academic achievement and cognitive abilities, which is moderated largely by the environment such that this mutual influence is more likely to occur in relatively richer as opposed to poorer environments (Tucker-Drob et al., 2013). Two related but relatively independent environmental factors are often considered: schooling and learning experiences/opportunities associated with family SES (Armor, Marks, & Malatinszky, 2018).

Schooling, with its primary function of academic instruction, can well explain cognitive-academic bidirectional relations (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 serve as a long-term training for cognitive abilities as well. Following this logic, the bidirectional relations between cognitive abilities and reading/mathematics may be most obvious during elementary and secondary schooling, where reading and mathematics are systematically taught and intensively practiced (Peng et al., 2019). Indeed, this hypothesis can help explain the stronger bidirectional relations between academic achievement and reasoning among children than among adolescents/adults from longitudinal data (Ferrer et al., 2007; Ferrer et al., 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 and opportunities associated with SES also greatly influence bidirectional relations between cognitive abilities and academic performance. In high-SES contexts, children have abundant opportunities for positive learning experiences, whereas in low-SES contexts, there are much fewer learning opportunities (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, Bøg, Filges, & Klint Jørgensen, 2017; Jacob & Parkinson, 2015). However, such early academic intervention effects generally fade after the intervention (Jenkins et al., 2018), and such fade-out outcome is more likely in those with very low academic skills before treatment (Bailey et al., 2016). These findings, together with the null findings for cognitive-academic bidirectional relations among children with learning disabilities based on longitudinal data (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) at the early development stage are more likely to trigger and benefit from cognitive-academic bidirectionality. That said, it has also been 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).

Taken together within the transactional model, all of these points have important implications for education and cognitive training. On the one hand, sustained, high-quality schooling/education especially in the primary and secondary stages not only fosters children's academic and cognitive development directly, but also contributes 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 cognitive-academic bidirectionality. On the other hand, the relations between reading/mathematics and working memory/reasoning/executive function are moderate (*r*s = .30~.45, 10~20% variance overlap; Jacob & Parkinson, 2015; Peng et al., 2019), and the effect of age on these relations is rather small, though significant (Peng et al., 2018; Peng et al., 2019). Thus, short-term cognitive training may be insufficient to improve academic performance. Long-lasting learning or the continued experiences of exercising reading and mathematics skills at school may be the ideal approach to improving both cognitive abilities and academic skills in most children (Ceci & Williams, 1997).

Conclusions and Recommendations for Future Studies

In sum, meta-analyses have provided evidence that the relations between reading/mathematics and working memory/reasoning increase with age, but age effects were not clear for relations involving executive functions. Reading/mathematics and working memory/reasoning/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 exerted positive effects on 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 are in need of further investigation to better understand these relationships.

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, these are based mostly on meta-analyses rather than in single large-scale cross-sectional empirical studies (although see Hofman et al., 2019). Evidence from large cross-sectional studies would circumvent the potential limitation of heterogeneity of methods and measures that could affect findings from meta-analyses and reviews. Such studies, as well as large longitudinal studies (Molenaar, 2004) are needed to investigate whether age is indeed associated with changes in the association between cognitive abilities and academic achievement. However, we note that 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 modelled effects, the magnitude of autoregressive paths and time-varying disturbances all can, and do, affect (cross-sectional and longitudinal) correlations so that they can increase, decrease or remain static depending on the precise causal mechanisms at play.

It is also necessary to consider possible 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 separate, discrete entities. Cognitive ability measures often invariably tap aspects of achievement skills (e.g., verbal/numerical working memory measures often tap language/reading/numerical knowledge heavily, especially for young children) and achievement tests often measure aspects of cognitive abilities (e.g., phonological awareness/reading comprehension often taps working memory, reasoning, and executive function). In this regard, there are no pure measures of cognitive abilities or academic achievement. 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 in fact tap multiple 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 can 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 shows a slower, longer developmental trajectory until late adolescence (Best & Miller, 2010; Zelazo & Carlson, 2012). Executive functions that do not include motivation/emotion processing tend to mature faster than executive functions that do (e.g., self-regulation/control; Zelazo & Carlson, 2012). Thus, inconclusive effects of age on the relation between executive functions and academic performance may be better explained and investigated further with consideration of executive function measurement and development.

We should also consider moderators on the bidirectional relations. The studies by Ferrer et al. (2007, 2010) show that although a bidirectional relation exists between IQ and reading during development, IQ seems to be driving this relation, partly in line with investment theory (academic skills develop through the investment of cognitive abilities). Similarly, although Schmitt et al. (2017) found a bidirectional relation between mathematics and executive function during the preschool years, they also found that, starting with kindergarten, only executive function predicted mathematics performance. Moreover, evidence from longitudinal designs 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/moderated by developmental stages, domains of academic skills, types of cognitive skills, and academically relevant social-emotional factors.

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