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Early Executive Function Predicts Reasoning Development

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Abstract

Analogical reasoning is a core cognitive skill that distinguishes humans from all other species and contributes to general fluid intelligence, creativity, and adaptive learning capacities. Yet its origins are not well understood. In the study reported here, we analyzed large-scale longitudinal data from the Study of Early Child Care and Youth Development to test predictors of growth in analogical-reasoning skill from third grade to adolescence. Our results suggest an integrative resolution to the theoretical debate regarding contributory factors arising from smaller-scale, cross-sectional experiments on analogy development. Children with greater executive-function skills (both composite and inhibitory control) and vocabulary knowledge in early elementary school displayed higher scores on a verbal analogies task at age 15 years, even after adjusting for key covariates. We posit that knowledge is a prerequisite to analogy performance, but strong executive-functioning resources during early childhood are related to long-term gains in fundamental reasoning skills.

Keywords

cognitive development, reasoning

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Innovation and adaptive thinking are hallmarks of 21st-century learning and essential for a modern workforce (National Research Council, 2012). Nonetheless, little is known about the cognitive mechanisms underlying children's development of the capacity to engage in these complex forms of reasoning. We used longitudinal data to suggest an integrated resolution to debates about the factors underlying children's acquisition of analogical thinking, one type of complex reasoning. Analogical reasoning is a core part of human innovation (Markman & Wood, 2009), creativity (Dunbar, 1997; Sternberg, 1988), and adaptive general intelligence (Cattell, 1971; Gentner, 2010). It is defined as the ability to draw relationships between disparate or dissimilar phenomena (Gentner, 1983). Thinking relationally is fundamental to analytical and inductive reasoning and may distinguish human thought from the thinking of humanity's closest animal relatives (Gentner, 2010; Penn, Holyoak, & Povinelli, 2008).

In the research reported here, we examined the specific contribution of early executive function to the development of analogical-reasoning skills, while taking into account proposed alternative mechanisms to the extent possible. Cross-sectional experimentation provides strong evidence that executive function plays a role in analogy development (Richland, Morrison, & Holyoak, 2006; Thibaut, French, & Vezneva, 2010). Executive function, also known as cognitive control, is generally defined as the ability to control cognitive actions. This includes both inhibiting impulsive task responding and manipulating and organizing complex information while holding it active in working memory. Executive function thus allows such complex skills as planning, monitoring, task switching, and controlling attention (Diamond, 2002; Stuss, 2007).

Inhibitory control and additional working memory aspects of executive function have been posited to explain analogical-reasoning capacity in children (Richland et al., 2006; Thibaut et al., 2010) and adults (Krawczyk et al., 2008). Neurological studies of analogy tasks have shown involvement of regions of the frontal lobe attributed to executive function (Bunge, Wendelken, Badre, & Wagner, 2005; Krawczyk et al., 2008). Executive function further predicts some aspects of school achievement (e.g., Bull, Espy, & Wiebe, 2008) and fluid intelligence (see J. Duncan, 2005). Executive function is also integral to the arc of reasoning skill across the life span, increasing with age in childhood and decreasing into old age, particularly from age 55 and above (Nettelbeck & Burns, 2009).

Several alternative theories of analogical-reasoning development have been proposed. Halford and colleagues (e.g., see

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Andrews & Halford, 2002) instead posit the relational-complexity theory, hypothesizing that the level of maturation in children's short-term and working memory may explain the number of relations that children can handle when thinking analogically—thus, younger children have more limited resources with which to complete a complex analogy. In our analysis of analogy development, we included short-term memory as a predictor to distinguish the role of higher-level executive-function processes (cognitive and inhibitory control in working memory) from the role of storage-capacity limits (short-term memory).

Other theories emphasize the role of knowledge acquisition. Goswami (1992) proposed the relational-primacy theory, which describes analogical reasoning as available to children from birth but limited by their knowledge. Gentner and Rattermann (1991) chart the trajectory of analogy development through relational-shift theory, hypothesizing that children will reason nonanalogically about representations before acquiring relevant background knowledge, connecting entities on the basis of appearance-based similarities. Then, following relevant knowledge acquisition, children will shift to analogical reasoning. These two theories propose different trajectories of analogy production but concur that base knowledge dictates a child's capacity. In the current study, a vocabulary assessment was used as a measure of children's base level of knowledge because analogical reasoning is closely tied to knowledge through language skills (see Gentner, 2010).

We have argued previously that these theories should not be considered mutually exclusive but rather may be operating concurrently (Morrison, Doumas, & Richland, 2011; Richland et al., 2006). However, in the current analysis, we were for the first time able to evaluate the long-term impact of one developmental mechanism, executive function, in the context of other proposed mechanisms, short-term memory-capacity limits and base knowledge. Specifically, we examined the long-term impact of early executive-function skills, both as a composite and specifically as inhibitory control, on the development of analogical reasoning from young childhood to adolescence. Reasoning in adolescence is particularly important because this is when youth encounter their most complex learning opportunities at school (e.g., Richland, Zur, & Holyoak, 2007), take college preparatory exams, and make important life-course decisions.

Method

Participants

The sample included 1,364 children (48% female, 52% male) participating in the Study of Early Child Care and Youth Development (SECCYD), of whom 539 had complete data on all variables used in the analysis. Multiple imputations were used to impute data for the missing variables for the remaining sample. The sample was diverse in terms of socioeconomic status (11% poor, i.e., income/poverty threshold < 1.5; 26% low or middle income, i.e., 1.5 < income/poverty threshold < 3; 63% middle or high income, i.e., income/poverty threshold > 3), ethnicity (76% White, 13% Black, 6% Hispanic, 5% other), and maternal education (18% had a high school diploma or less, 35% had some college, 26% had a bachelor's degree, and 15% had a graduate degree).

Procedure

A select subset of the SECCYD measures were included in the current analysis. These assessments are described in more detail on the SECCYD Web site (http://secc.rti.org).

Analytical reasoning. Reasoning skill was examined as a dependent measure using the Verbal Analogies subtest (VA) of the Woodcock-Johnson Psycho-Educational Battery–Revised (WJ-R; Woodcock & Johnson, 1990) at third grade and at age 15 years. Analogies on the WJ-R VA were presented orally at third grade and in written form at age 15 years, in the traditional form of "a is to b as c is to d" (e.g., "dog is to puppy as cat is to ___?"). The child is shown pictures of objects and required to select the object that best completes the analogy. As a language-based, formal-analogy task, versus a nonverbal or problem-solving task, this measure relies on a combination of reasoning skill and vocabulary. The inclusion of a vocabulary measure as a predictor was therefore essential to evaluating the distinct role of executive function.

Executive function. Two measures of executive function were used. General executive-function capacity was assessed using the Tower of Hanoi (TOH) task (as adapted from Borys, Spitz, & Dorans, 1982) at first grade. This task requires the integration of component executive-function skills: inhibitory control, goal shifting, and manipulating information held in a mental set (Bull, Espy, & Senn, 2004; Miyake et al., 2000). The task required children to move a configuration of objects from one peg to another without violating constraining rules; a composite efficiency score was calculated based on performance over six trials. The second task, the Children's Stroop, administered at age 54 months, focused on inhibitory control—the executive-function ability to monitor and control automatic responses to stimuli. Children were shown cards of day or night pictures and were instructed to respond "day" to the night pictures and vice versa (Gerstadt, Hong, & Diamond, 1994).

Vocabulary knowledge. A vocabulary score at age 54 months was included as a measure of acquired verbal knowledge that might serve as a prerequisite to analogical reasoning (Gentner & Rattermann, 1991; Goswami, 1992). Standard scores on the WJ-R Picture Vocabulary subtest (WJ-R PV; Woodcock & Johnson, 1990) measured children's ability to recognize or name picture objects.

Short-term memory. The standard score on the WJ-R Memory for Sentences subtest (WJ-R MS; Woodcock & Johnson, 1990) measured children's ability at age 54 months to remember and repeat simple words, phrases, and sentences presented verbally. A short-term memory measure allowed us to distinguish between the contributions of simple storage capacity and active manipulation in executive function.

Sustained attention. The Continuous Performance Test (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) was administered at age 54 months as a measure of children's vigilance and ability to sustain attention on a task. The CPT has been used to assess attention disorders that could involve executive-function processes. However, component analyses suggest that it is most directly a test of vigilance and ability to sustain attention, rather than a test of cognitive flexibility or control (Mirsky, Anthony, Duncan, Ahearn, & Kellam, 1991). Thus, in this study, the CPT was used as a covariate to distinguish between the effects of vigilance and executive function.

Demographic family characteristics. Data were collected on family background via interviews conducted with mothers. The recruitment site was considered families' geographical location. Mothers reported the child's ethnicity (coded as white, black, Hispanic, or other), child's gender, the mother's years of education, family income, and household size. Socioeconomic status was calculated as an income-to-needs ratio by dividing total family income by the relevant poverty line for family income established by the U.S. Office of Management and Budget.

Data analysis

Analyses of covariance (ANCOVA) predicted analogical reasoning at age 15 years from early executive-function, vocabulary, memory, and attention skills, adjusting for analogical reasoning in third grade and family characteristics. In other words, this analysis tested the extent to which residualized increases in analogical-reasoning scores on the WJ-R from age 10 to age 15 years varied as a function of selected early school-age skills. All measures were included as predictors. The scores on the Children's Stroop, CPT, and TOH were skewed toward zero, and a square-root transformation was applied to reduce the skew. The covariates included the child's WJ-R analogical-reasoning score in third grade and the child's gender, mother's education, family income, child's ethnicity, and recruitment site. Effect sizes were computed by multiplying the unstandardized coefficient yielded in the analysis by the standard deviation on the predictor and dividing the result by the standard deviation of the outcome (National Institute of Child Health and Human Development Early Child Care Research Network & Duncan, 2003).

The inclusion of the child's analogical-reasoning skills in third grade as a covariate allowed us to test the extent to which skills in the other measured areas at entry to school contributed to predicting the variability in the youth's analogical-reasoning skills at age 15 years that was not related to his or her skills at age 10 years. The inclusion of analogy skill at third grade as a covariate made the analysis of the other predictors relatively conservative because analogy skill was measured at a later age. Therefore, observed associations reflect the extent to which early childhood skills predict gains over time beyond their ability to predict the child's skill level in third grade.

Not surprisingly, there were missing data in the 15-year longitudinal study. Multiple imputations were conducted to estimate missing data in a manner that approximated both the value of a missing variable for that individual from all other data and the degree of variability in the variable (Widaman, 2006). Fifteen data sets were imputed from all of the variables in the analysis plus measures of family income and parenting during early and middle childhood. The efficiency in imputing all analysis variables exceeded .90. Each of the imputed data sets was analyzed using ANCOVAs, and the parameters and their standard errors were combined to reflect variability within and between data sets.

Results

Descriptive statistics for the entire sample are shown in Table 1, and correlations among all analyzed variables are presented in Table 2. Verbal Analogies scores at 15 years of age were moderately to highly correlated with the selected family covariates and earlier vocabulary, attention, memory, and executive-function measures. Most of these measures of the child's skills were modestly correlated, with somewhat higher correlations among the various subtests of the WJ-R.

Regression analyses provided a relatively stringent test of the contribution of executive function, vocabulary, memory, and attention skills to the development of analogical-reasoning skills between the ages of 10 and 15 years (Table 3). An ANCOVA indicated that most of the selected covariates—earlier Verbal Analogies score, maternal education, location: $F(9, 1342) = 2.91$, $p < .001$, and ethnicity: $F(3, 1342) = 9.30$, $p < .001$—were significantly related to verbal-analogy skills at age 15 years. Child gender ($p = .11$) and family income ($p = .77$) were not. Adjusting for these covariates and all other earlier child skills in the model, we found that verbal-analogy skills at age 15 were independently predicted from the executive-function skills in first grade (as measured by the TOH task: $p < .012$) and inhibitory-control skills at entry to school (as measured by the Children's Stroop: $p < .023$) as well as vocabulary ($p < .001$). The child's short-term memory ($p = .41$) and skills at sustaining attention ($p = .07$) were not reliably related to verbal-analogy skills at age 15 years.[1] The magnitude of the associations tended to be small but reliable, as illustrated in Figure 1, which shows the predicted score for children who scored 1 standard deviation below the mean, at the mean, and 1 standard deviation above the mean on measures of vocabulary skills at 54 months, inhibitory control at 54 months, and executive function at the first grade.

To evaluate the concern that executive function and vocabulary would successfully predict a wide range of outcome measures, we ran the same model again twice, predicting outcomes that were not theorized to require these executive functions of

Table 1. Descriptive Statistics for the Study Variables

Variable	*n*	*M*	*SD*	Range
Verbal analogies				
WJ-R Verbal Analogies: 15 years	891	113.70	16.10	68–167
WJ-R Verbal Analogies: Grade 3	1,013	109.21	17.23	50–163
Demographic characteristics				
Child gender (male = 1, female = 0)	1,364	0.52		
Mother's years of education	1,363	14.23	2.51	7–21
Family income-to-needs ratio	1,073	3.59	3.17	0.10–57.0
Predictors				
Vocabulary (WJ-R Picture Vocabulary): 54 months	1,060	100.24	15.03	10–143
Inhibitory control (Children's Stroop): 54 months	838	25.34	20.53	0.0–87.5
Executive function (Tower of Hanoi): Grade 1	998	14.38	6.76	0–34
Sustained attention (CPT): 54 months	1,002	9.13	7.59	0–41
Short-term memory (WJ-R Memory for Sentences): 54 months	1,054	91.74	18.49	17–142

Note: Mother's years of education and family income-to-needs ratio were measured when children were 1 month old and 54 months old, respectively. Predictors were measured using the Woodcock-Johnson Psycho-Educational Battery–Revised (WJ-R; Woodcock & Johnson, 1990), Children's Stroop test (Gerstadt, Hong, & Diamond, 1994), Tower of Hanoi task (as adapted from Borys, Spitz, & Dorans, 1982), and Continuous Performance Test (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956).

cognitive inhibitory control or analogical reasoning. We ran the model first with reading comprehension as an alternative achievement outcome and second with externalizing behavior as an alternative behavioral outcome. Although both academic and externalizing behaviors have been shown to be related to behavioral control over sustaining attention to task as measured by the CPT (G. J. Duncan et al., 2007), this construct is distinct from executive function as defined here (i.e., response inhibition and the ability to manipulate information in working memory; see Diamond, 2002; Miyake et al., 2000; Stuss, 2007).

In these additional analyses, neither executive-function variable predicted reading (Children's Stroop: $\beta = -0.02$, $SE = 0.04$, $p = .54$; TOH: $\beta = 0.04$, $SE = 0.03$, $p = .14$) or behavior problems (Children's Stroop: $\beta = 0.02$, $SE = 0.02$, $p = .40$; TOH: $\beta = -0.03$, $SE = 0.04$, $p = .51$). In contrast, reading was predicted by vocabulary scores ($\beta = 0.48$, $SE = 0.03$, $p < .001$) and short-term memory ($\beta = 0.08$, $SE = 0.03$, $p = .017$), and externalizing behavior was predicted by sustained attention ($\beta = 0.07$, $SE = 0.04$, $p = .04$)

Discussion

Overall, these results indicate that both inhibitory control and composite executive-function skills make independent, specialized contributions to children's analytical-reasoning development beyond the contributions of key cognitive and environmental covariates, as we hypothesized from cross-sectional and simulation data (Morrison et al., 2011; Richland et al., 2006). The significant relationship between early vocabulary and later reasoning skill additionally supports theoretical

Table 2. Correlations Among Major Study Variables

Variable	1	2	3	4	5	6	7	8
1. Verbal Analogies: 15 years	—							
2. Verbal Analogies: Grade 3	.64***	—						
3. Maternal education	.42***	.36***	—					
4. Income-to-needs ratio: 54 months	.26***	.20***	.49***	—				
5. Vocabulary: 54 months	.46***	.42***	.41***	.31***	—			
6. Inhibitory control: 54 months	−.19***	−.12**	−.12***	−.11**	−.08*	—		
7. Executive function: Grade 1	.26***	.22***	.15***	.14***	.19***	−.04	—	
8. Sustained attention: 54 months	−.24***	−.23***	−.17***	−.13***	−.25***	.08*	−.23***	—
9. Short-term memory: 54 months	.37***	.39***	.28***	.23***	.46***	−.08*	.22***	−.24***

*$p < .05$. **$p < .01$. ***$p < .001$.

Table 3. Results From the Analysis of Covariance Predicting Verbal Analogy Skills at 15 Years From Early Test Performance

Variable	β	*b*
Intercept	29.67 (4.79)	
Covariates		
Child gender (male = 1, female = 0)	1.11 (0.70)	0.03
Mother's years of education	1.07** (0.22)	0.17
Family income-to-needs ratio: 54 months	0.04 (0.15)	0.01
WJ-R Verbal Analogies: Grade 3	0.44*** (0.03)	0.47
Predictors		
Vocabulary (WJ-R Picture Vocabulary): 54 months	0.12*** (0.03)	0.11
Inhibitory control (Children's Stroop): 54 months (square root)	−0.42* (0.18)	−0.06
Executive function (Tower of Hanoi): Grade 1 (square root)	1.17* (0.46)	0.07
Sustained attention (CPT): 54 months (square root)	−0.59 (0.32)	−0.05
Short-term memory (WJ-R Memory for Sentences): 54 months	0.02 (0.03)	0.03

Note: Standard errors are given in parentheses. The model was also adjusted for the site at which participants were recruited and participants' race or ethnicity. Predictors were measured using the Woodcock-Johnson Psycho-Educational Battery–Revised (WJ-R; Woodcock & Johnson, 1990), Children's Stroop test (Gerstadt, Hong, & Diamond, 1994), Tower of Hanoi task (as adapted from Borys, Spitz, & Dorans, 1982), and Continuous Performance Test (CPT; Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956).
$^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

proposals that language and knowledge are necessary underpinnings for verbal analogical reasoning (Gentner & Rattermann, 1991; Goswami, 1992), but knowledge alone cannot explain these children's long-term gains in reasoning skills. Inhibitory-control skills may be particularly influential, because they were a distinct predictor of children's analogy development from the composite executive-function task.

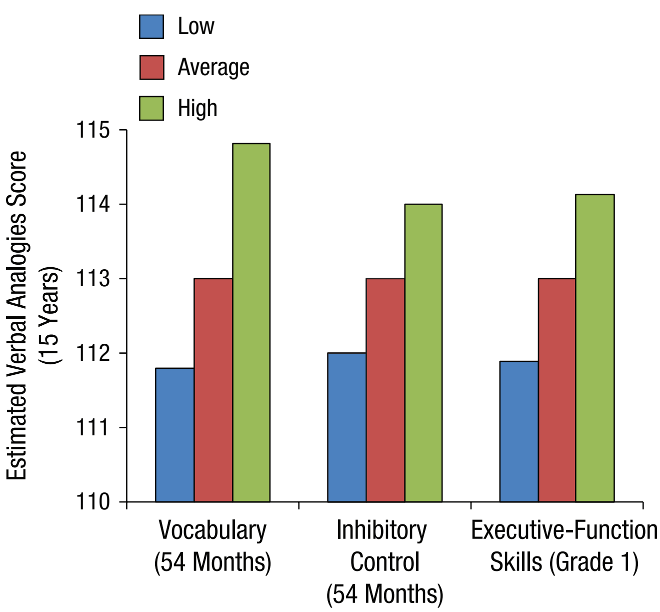

Fig. 1. Estimated Verbal Analogies score at age 15 years as a function of early vocabulary, inhibitory control, and executive-function skills (low = 1 *SD* below the mean; high = 1 *SD* above the mean). Estimates were adjusted for other covariates.

These results provide further evidence that strengthening early executive-function skills (see Diamond & Lee, 2011), particularly inhibitory control, should be part of the growing national discourse around early childhood education as a tool to maximize children's potential for future academic and professional success. Supporting the development of analogical reasoning may help students become more innovative, adaptive, and intelligent, which are qualities necessary for success in the global economy today (National Research Council, 2012).

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Note

1. The CPT significantly predicted analogical reasoning in the model when the other executive-function measures were removed. This fact reinforces the interpretation that the CPT is a better measure

of vigilance and the ability to sustain attention than of executive-function skills broadly, as indicated by the literature, though it does account for some of the same variance.

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