Exploring the Foundations of Causal Reasoning in 3-and 5-year-old Children

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Abstract

The goal of this study was to identify potential cognitive components of causal reasoning (CR) and to investigate their developmental trajectory in early childhood. We specifically focused on executive function (EF) as a potentially fundamental predictor of CR. While previous research has demonstrated that EF is related to achievement in other academic domains such as reading and math, relatively little attention has been paid to its relationship to scientific processes like CR, particularly in early childhood. To examine how EF potentially relates to the development of CR, we recruited 140 3-year-olds and 81 5-year-olds to complete two CR tasks, a battery of EF tasks, and additional cognitive measures. Results from a series of multiple regressions revealed that EF predicted contemporaneous CR, even after controlling for the influence of age, processing speed, and vocabulary knowledge. However, less variance than expected was accounted for by EF and additional covariates. Although additional research will be required to further clarify these relationships, the current results suggest that EF has the potential to support CR. Results are discussed in the broader context of scientific literacy.

Introduction and Background

In this paper, we examine whether executive function (EF) has the potential to support the emergence of causal reasoning (CR) by evaluating patterns of correlation across a marked developmental transition. We focus on early CR because it has the potential to serve as a critical foundation for scientific literacy. Indeed, at the very core of scientific endeavor is an understanding of causality, underlying the ability to make predictions, test hypotheses, and interpret evidence. We know that even preschoolers are able to engage in at least some forms of CR (e.g., Gopnik & Schulz, 2007). Yet little is known about individual differences in early emerging CR skills, or about their relationship to other cognitive processes which are undergoing simultaneously rapid development. Specifically, we ask whether CR a unique capability that develops relatively independently or whether it is largely dependent on broader, more fundamental, cognitive abilities? EF is an especially promising contributor based on its already established role in the development of core academic domains like reading and math (Best, Miller, & Naglieri, 2011; Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; St Clair-Thompson & Gathercole, 2006). Although its relevance to understanding processes in the scientific domain has received relatively little attention (Gropen, Clark-Chiarelli, Hoisington, & Ehrlich, 2011; Zaitchik, Iqbal, & Carey, 2014), EF has been associated with a broad array of related cognitive skills such as planning and goal directed problem solving (Best et al., 2011; Blair & Razza, 2007; Brock et al., 2009; Diamond, 2013).

Methods

Participants

Data for this study were collected as part of a larger longitudinal study investigating the development of children's interest in causal information. Our study sample included 221 children (140 = 3-year-olds; 81 = 5-year-olds) from the Austin, Texas area. Participating children were three or five years of age at the first session (M_3 = 40.89 mo; SD_3 = 3.15 mo, range = 36.14-47.27 mo, 77= female; M_5 = 65.19 mo; SD_5 = 3.79 mo, range = 56.24-71.98 mo, 45 = female). Children did not have any diagnosed developmental delays or disorders, and they understood English "well" or "very well" as reported by a parent. The sample was racially, ethnically, and socioeconomically representative of our recruitment area.

Measures

To begin exploring this potential relationship, we assessed three- and five-year-olds' performance on two CR tasks (causal inference and counterfactual reasoning), each of which we expected might be influenced in different ways by distinct EF skills. The causal inference task (Das Gupta & Bryant, 1989) required children to compare pictures taken before and after a transformation (e.g., broken flowerpot and intact flowerpot) and to select a tool (e.g., glue) that could have caused it. The counterfactual reasoning task (Guajardo & Turley-Ames, 2004) required children to generate alternative courses of action that would lead to different outcomes in fictional vignettes. We measured EF with five tasks: flanker, black/white stroop, bear/dragon (inhibition), count/label (working memory), and dimensional change card sort (cognitive flexibility). Finally, we measured children's vocabulary and processing speed.

Procedure

Data for this study were collected over two to three sessions lasting approximately 45-60 minutes each. Sessions were audio-visually recorded for offline coding of participant responses and verification of protocol fidelity. The first session for three-year-olds took place at a local children's museum. All other sessions took place in our laboratory in a colorfully decorated room at a child-sized table. At the first session, parent consent was obtained and children were assessed on receptive language. Parents also completed a demographic interview.

Coding

Trained researchers scored the causal inference, counterfactual reasoning, count/label, black/white stroop, and bear/dragon tasks offline using video recordings. For all tasks, a second coder assessed 20% of files to ensure reliability of coding. The coders also assessed videos for fidelity to protocol on the bases of general procedures and adherence to a script (if applicable). There was excellent agreement for the dichotomous coding scheme used for the counterfactual reasoning task (Cohen's $\kappa = .93$ and .95, for 3- and 5-year-olds, respectively). All four measures from the NIH-TB were automatically scored. Participant data were coded and managed using REDCap (Research Electronic Data Capture) hosted at University of Texas at Austin (Harris et al., 2009).

Results

All data analyses were conducted using RStudio (R version 1.0.136; RStudio Team, 2016; R Core Team, 2016). Rates of missing data range from 0% to 16.28% (see Table 1) across tasks. To handle missing data in our regression analyses, we employed multiple imputation (MI) using the "mice" package that also runs in RStudio (Brand, 1999; van Buuren & Groothuis-Oudshoorn, 2011).

Before conducting any analyses on this imputed data, we scaled individual EF and causal reasoning measures ($M = 0$, range: -3, 3) for each age group separately. Then, we created a composite EF variable from all of the EF tasks including count/label, flanker, stroop, bear/dragon, and DCCS tasks. Our dependent causal reasoning variable for all analyses is a composite score made from the causal inference and counterfactual reasoning tasks.

The means, standard deviations, and ranges for age, vocabulary, EF measures, and CR measures are displayed in Tables 2 and 3. Simple bivariate correlations between these variables of interest are presented in Tables 4 and 5. A linear regression was used to determine whether EF accounted for a significant proportion of variance in 3-year-olds' causal reasoning ability. Child age, vocabulary, and processing speed were entered as covariates. The model accounted for a significant proportion of variance, $R^2 = 0.30$, $F(4, 647.17)$[1] $= 10.45$, $p < .001$. All variables except processing speed were significant predictors of causal reasoning (see Table 6). A parallel model applied to the 5-year-old data also accounted for a significant proportion of variance, $R^2 = 0.54$, $F(4, 21.61)$[1] $= 12.01$, $p < .001$. However, all variables except child age were significant predictors for this age group (see Table 7).

Discussion

As hypothesized, we found that EF was a significant predictor of both 3- and 5-year olds' CR ability, as measured by a causal inference/counterfactual reasoning composite score. These results are in line with previous work that has shown that working memory capacity (Drayton, Turley-Ames, & Guajardo, 2011; Guajardo, Parker,

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[1] The F-test was calculated using the function micombine.F() from the 'miceadds' package in R. The function uses a combination of F statistics for multiply imputed datasets using a chi square approximation.

& Turley-Ames, 2009) and inhibition (Beck, Riggs, & Gorniak, 2009) in young children are related to their performance on counterfactual reasoning tasks. Similar relationships between EF and general reasoning abilities have also been shown in older children, adolescents (De Neys & Everaerts, 2008; Handley, Capon, Beveridge, Dennis, & Evans, 2004; Simoneau & Markovits, 2003), and young adults (e.g., Markovits & Doyon, 2004).

That said, the measures included in our models only accounted for 30 and 54% of the variance in CR for 3- and 5-year-olds respectively. This degree of unaccounted for variance could be taken as evidence that CR is a unique capability that is not wholly emergent from more fundamental cognitive skills, and therefore develops with some degree of independence. Before reaching this conclusion, however, it will be important to consider other potential contributors to the development of CR (e.g., motivational or experiential factors) that were not assessed in this study.

In summary, this study found that EF significantly predicted CR performance across a period of rapid developmental change in both sets of skills from 3- to 5-years of age. However, a significant amount of variance in children's CR performance remained unaccounted for by EF and our other cognitive covariates (i.e., vocabulary and processing speed), thereby leaving open the possibility that some aspect of CR develops as a distinct capability. These results provide an important foundation for understanding the development of CR in the context of broader cognitive skills and academic performance. For example, CR is likely a critical component of scientific literacy (Bauer & Booth, under review). Despite research demonstrating that achievement gaps in science begin to form before children even enter school (Greenfield et al., 2009), preschool classrooms typically do not focus on science. In part, achievement gaps in science may persist because we still know little about what knowledge and skills are fundamental to scientific literacy, and therefore would be most usefully targeted in early education. This study has begun to address this limitation by examining the developmental relationship between CR and EF, two possible underlying contributors to scientific understanding.

Tables

Table 1. Rates of Missingness for Each Study Variable for Final Sample.

	% Missing	
Variable	3-year-olds	5-year-olds
Vocabulary	0	9.23
Processing Speed	16.28	4.62
Count/Label	12.07	1.54
Flanker	6.90	4.62
Stroop	11.21	1.54
Bear/Dragon	12.07	4.62
DCCS	15.52	1.54
CI	6.90	0
CFR	8.62	12.31

Note. DCCS = Dimensional Change Card Sort; CI = causal inference; CFR = counterfactual reasoning.

Table 2. Descriptive Statistics for Three-Year-Old Data After Imputation.

Variables	Mean	SD	Min	Max
Age	40.97	3.17	36.17	47.27
Vocabulary	57.26	6.37	37	88
Processing Speed	48.29	8.42	31	74
Count/Label	0.79	0.90	0	2
Flanker	38.75	12.93	22	87
Stroop[a]	0.44	0.33	0	1.00
Bear/Dragon	3.66	1.93	0	5
DCCS	47.80	13.53	34	84
CI	4.71	1.84	0	8
CFR	1.35	1.32	0	4

Note. DCCS = Dimensional Change Card Sort; CI = causal inference; CFR = counterfactual reasoning. [a]Proportion correct.

Table 3. Descriptive Statistics for Five-Year-Old Data After Imputation.

Variables	Mean	SD	Min	Max
Age	65.21	3.56	60.22	71.98
Vocabulary	68.09	7.71	52	91
Processing Speed	64.57	10.88	43	88
Count/Label	1.62	0.70	0	2
Flanker	68.80	17.26	24	92
Stroop[a]	0.66	0.29	0	1
Bear/Dragon	4.72	0.78	0	5
DCCS	71.60	16.21	38	96
CI	6.98	1.19	2	8
CFR	2.80	1.33	0	4

Note. DCCS = Dimensional Change Card Sort; CI = causal inference; CFR = counterfactual reasoning. [a]Proportion correct.

Table 4. Correlations Between Main Study Variables for Three-Year-Olds After Imputation

	Age	Vocab.	Speed	Count	Flanker	Stroop	Bear	DCCS	CI
Age									
Vocab.	0.25**								
Speed	0.26*	0.25**							
Count	0.22*	$0.17^{\dagger}$	0.44***						
Flanker	0.25**	0.23*	0.07	0.3**					
Stroop	0.13	$-0.16^{\dagger}$	0.09	$0.19^{\dagger}$	$0.2^{\dagger}$				
Bear	$0.18^{\dagger}$	0.22*	0.27*	$0.21^{\dagger}$	0.06	0.05			
DCCS	0.16	0.04	-0.14	0.08	0.23*	0.09	0.08		
CI	0.3**	0.41***	0.15	$0.18^{\dagger}$	0.25**	0.23*	0.19*	0.07	
CFR	0.35**	$0.18^{\dagger}$	0.23*	0.27**	0.15	0.07	$0.19^{\dagger}$	0.08	0.26**

Note. Simple correlation coefficients are shown; CI = causal inference; CFR = counterfactual reasoning; Speed = processing speed; $^{\dagger}p$<0.1; *p<0.05; **p<0.01; ***p<0.001.

Table 5. Correlations Between Main Study Variables for Five-Year-Olds After Imputation.

	Age	Vocab	Speed	Count	Flanker	Stroop	Bear	DCCS	CI
Age									
Vocab	$0.24^{\dagger}$								
Speed	0.05	0.11							
Count	0.27*	0.48***	0.39**						
Flanker	0.32**	0.3*	0.42***	0.29*					
Stroop	0.3*	0.13	-0.01	0.16	$0.25^{\dagger}$				
Bear	0.11	$0.24^{\dagger}$	0.1	0.18	$0.24^{\dagger}$	$0.24^{\dagger\dagger}$			
DCCS	0.11	0.48***	0.32*	0.34**	0.45***	0.13	$0.23^{\dagger}$		
CI	0.31*	0.53***	0.36**	0.4***	0.51***	0.33**	0.43***	0.32**	
CFR	0.28*	0.41***	0.35**	0.5***	0.28*	0.11	0.26*	0.2	0.42***

Note. Simple correlation coefficients are shown; CI = causal inference; CFR = counterfactual reasoning; Speed = processing speed; $^{\dagger}p$<0.1; *p<0.05; **p<0.01; ***p<0.001.

Table 6. Regression Results for Three-Year-Olds Predicting the Causal Reasoning Composite Variable.

	Dependent variable: CR composite variable			
Variable	*B*	SE(*B*)	*t*-value	*p*-value
Age	0.25	(0.09)	2.70	0.01
Vocabulary	0.25	(0.09)	2.79	0.01
Processing Speed	0.07	(0.10)	0.68	0.50
EF	0.23	(0.09)	2.56	0.01

Note. $R^2 = 0.30$; *B* = unstandardized coefficients for standardized variables; standard errors are reported in parentheses; CR = causal reasoning; EF = executive function.

Table 7. Regression Results for Five-Year-Olds Predicting the Causal Reasoning Composite Variable.

	Dependent variable: CR Composite Variable			
Variable	*B*	SE(*B*)	*t*-value	*p*-value
Age	0.15	(0.10)	1.50	0.14
Vocabulary	0.32	(0.11)	2.90	0.01
Processing Speed	0.26	(0.10)	2.56	0.01
EF	0.31	(0.12)	2.53	0.01

Note. $R^2 = 0.54$; *B* = unstandardized coefficients for standardized variables; standard errors are reported in parentheses; CR = causal reasoning; EF = executive function.

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