

BRIEF REPORT

Fine Motor Skills During Early Childhood Predict Visuospatial Deductive Reasoning in Adolescence

Robert A. Cortes¹, Adam E. Green^{1, 2}, Rachel F. Barr¹, and Rebecca M. Ryan¹¹ Department of Psychology, Georgetown University² Interdisciplinary Program in Neuroscience, Georgetown University

Extensive evidence and theory suggest that the development of motor skills during infancy and early childhood initiates a “developmental cascade” for cognitive abilities, such as reading and math. Motor skills are closely connected with the development of spatial cognition, an ability that supports deductive reasoning. Despite the linkage between motor skills and spatial cognition, and spatial cognition with deductive reasoning, no research has explored the developmental connection between early motor skills and reasoning ability, a plausible pathway through which the developmental cascade operates. Drawing data from the 1970 British Cohort Study ($N = 1,233$; 95% British, 5% other race/ethnicity; 54% male, 46% female; 7% low income, 80% middle income, 12% high income), this study investigated whether there was a relationship between gross and fine motor skills in infancy (22 months of age) and early childhood (42 months of age) and visuospatial deductive reasoning in adolescence (at 10 and 16 years of age). Results indicated that fine but not gross motor skills during early childhood positively predicted reasoning in adolescence. Critically, the fine motor-reasoning association mediated the previously observed link between early fine motor skills and adolescent reading and math ability. These results deepen our understanding of developmental cascade theory and mental model theory by identifying visuospatial reasoning (i.e., mental modeling) as a potential mechanism through which motor skills initiate cognitive development and academic success in reading and math. These findings also highlight the importance of early intervention programs targeting motor skills and illuminate the impact of those interventions on later cognitive and academic skills.

Keywords: motor skills, reasoning, developmental cascade, mental model theory, spatial cognition

Supplemental materials: <https://doi.org/10.1037/dev0001354.supp>

Motor skills develop rapidly from infancy through early childhood (Adolph & Berger, 2007; Goodway et al., 2019). During this time, children’s motor milestones are closely monitored by health care professionals to identify motor processing delays and, when detected, to provide early intervention services that aim to improve their motor outcomes (Mahoney et al., 2004). This is because early motor delays may be indicative of underlying developmental

disorders (e.g., autism spectrum disorder, Down’s syndrome, cerebral palsy; Mahoney et al., 2001; Ozonoff et al., 2008) and because early motor development presages later cognitive skills like reading and math (Adolph & Tamis-LeMonda, 2014; Bornstein et al., 2013; Piaget, 1952). Although the latter linkages are well established, the developmental mechanisms explaining them are far less clear.

Developmental researchers have theorized that reaching early developmental motor milestones may initiate a “developmental cascade” by allowing children to actively explore and navigate the world, facilitating later cognitive abilities and academic achievement (Adolph & Tamis-LeMonda, 2014; Bornstein et al., 2013; Gibson, 1988; Libertus et al., 2016; Piaget, 1952). Indeed, a robust literature supports the theory that early motor skills predict later cognitive ability: Specifically, gross motor skills (e.g., balance, walking) at 3–5 months of age predict attention at 8 years (Friedman et al., 2005) and academic achievement at 15 years (Bornstein et al., 2013). Fine motor skills at 2–4 years of age predict school readiness and academic achievement, especially in reading and mathematics, in 5- to 11-year-olds (Cameron et al., 2012; Dinehart

This article was published Online First March 31, 2022.

Robert A. Cortes  <https://orcid.org/0000-0003-1106-9452>

Rachel F. Barr  <https://orcid.org/0000-0002-5855-9718>

Rebecca M. Ryan  <https://orcid.org/0000-0002-3924-3574>

Data and study materials for all experiments are available from the U.K. Data Service (<https://ukdataservice.ac.uk/>). This study was not preregistered.

Correspondence concerning this article should be addressed to Robert A. Cortes, Department of Psychology, Georgetown University, White Gravenor Hall, 3700 O Street Northwest, Washington, DC 20057, United States. Email: rac114@georgetown.edu

& Manfra, 2013; Grissmer et al., 2010; Pagani & Messier, 2012; Son & Meisels, 2006). The exact mechanism by which early motor skills predict later reading and math ability is unknown, though many posit this developmental cascade could be bridged by visual or spatial processes that in turn promote reasoning skills more broadly (Cameron et al., 2016; Grissmer et al., 2010; Son & Meisels, 2006). Here, we argue that spatial reasoning (i.e., the ability to construct and manipulate mental models of information) may be a potential mechanism for the motor-cognitive developmental cascade between early fine motor skills and reading and math during adolescence.

Motor skills are closely connected with the development of spatial cognition, often defined as the ability to visualize and manipulate spatial information (Hart & Moore, 1973). In adults, researchers have found that spatial cognition (namely mental rotation) is consistently associated with both gross and fine motor skills, and a large body of evidence and theory suggest that motor processing mechanistically underlies spatial cognition (Ozel et al., 2004; Voyer & Jansen, 2017; Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998). Critically, this motor-spatial link exists as early as infancy and early childhood as better motor skills at ages 6–10 months and 5–6 years predict better spatial cognition (mental rotation; Frick & Möhring, 2013; Jansen & Heil, 2010; Lehmann et al., 2014; Möhring & Frick, 2013; Schwarzer et al., 2013). In fact, it has been posited that the overlap between motor and spatial processing may be strongest during early childhood and that these abilities begin to differentiate in adolescence and adulthood (Frick et al., 2009; Funk et al., 2005; Karmiloff-Smith, 2012).

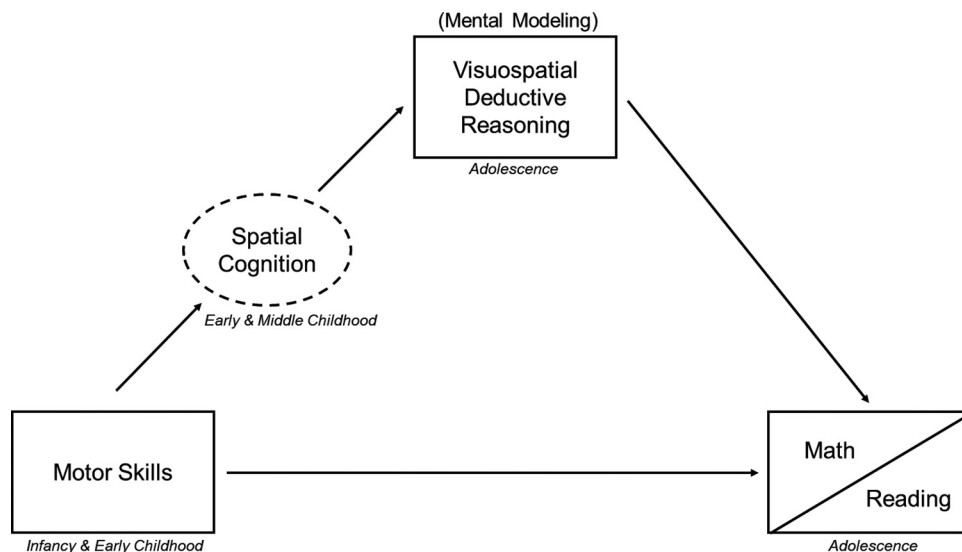
Extensive cognitive science research has demonstrated the link between spatial cognition and deductive reasoning (i.e., the ability to draw inferences and conclusions to solve problems; Johnson-Laird, 1980, 2004, 2010). Consistent with this evidence, mental model theory proposes that during deductive reasoning, humans

tend to envision and manipulate information in spatialized ways by creating visual representations, often called “mental models,” that allow them to evaluate and draw conclusions from complex situations (Johnson-Laird, 1980, 2004, 2010). Cognitive and brain-based research supports mental model theory in the context of both verbal and visuospatial deductive reasoning, consistently finding evidence for the role of spatial processes during reasoning (Goel et al., 2000; Johnson-Laird, 1980, 2004, 2010; Johnson-Laird et al., 2017; Khemlani & Johnson-Laird, 2012; Ragni & Knauff, 2013). Despite the robust evidence for the mental model theory in adults and older adolescents, no research to date has explored the developmental connection between spatial cognition and deductive reasoning across the life span (from birth to adulthood).

Given that motor skills (both gross and fine) are linked to spatial cognition in infancy through adulthood, and that spatial cognition supports visuospatial deductive reasoning, it is plausible that motor skills might also be associated with visuospatial deductive reasoning. Very little research has explored this topic, though one study demonstrated that practicing a musical instrument (a form of fine motor training) is associated with enhanced visuospatial deductive reasoning at 9 years of age (Forgeard et al., 2008), while another study found that gross motor skills at 6 years of age were associated with concurrent spatial reasoning ability (Frick & Möhring, 2015). Moreover, extensive literature has linked the motor system to mental simulation (Iani, 2019), an ability that could support the construction of mental models during reasoning. A key question is whether there exists a developmental connection between early motor skills and later visuospatial deductive reasoning ability.

Drawing on both the developmental cascade framework and mental model theory, we investigated the hypothesis that gross and fine motor skills during early childhood may predict visuospatial deductive reasoning ability during adolescence (see Figure 1). The development of spatial cognition presents a plausible mechanistic link

Figure 1
Theoretical Model for the Developmental Cascade Between Early Motor Skills and Later Reasoning, Math, and Reading Abilities in Adolescence



for this hypothesized cascade (see Figure 1) such that motor skills during infancy and early childhood support the development of spatial cognition during early and middle childhood, which then promotes visuospatial deductive reasoning during adolescence. More specifically, gross motor skills could be related to future reasoning given that the ability to differentiate between egocentric and allocentric spatial cognition may develop via gross motor actions and experiences that occur in a larger spatial context—this advanced spatial processing could support abstract visualization of physical content during deductive reasoning (Galati et al., 2000; Johnson-Laird, 2010; Klatzky, 1998). Fine motor skills could be related to future reasoning as this kind of motor processing allows children to practice mapping visual representations to emerging verbal and mathematical concepts (Cameron et al., 2016), which may allow for more fine-tuned mapping during mental model construction in deductive reasoning. Moreover, a large body of neuroscientific evidence indicates that motor skills, spatial cognition, and deductive reasoning all share common neural substrates in the premotor cortex, parietal cortex, and cerebellum (Cona & Scarpazza, 2019; Eslinger et al., 2009; Goel et al., 1998; Guell et al., 2018; Prabhakaran et al., 1997; Rizzolatti & Luppino, 2001; Rowe et al., 2002; Wertheim & Ragni, 2018; Wise et al., 1997).

Critically, it is possible that the link between early motor skills and visuospatial deductive reasoning in adolescence could be a potential mechanism for the developmental cascade between early motor skills and later math and reading performance (see Figure 1). Prior evidence suggests that the mental modeling ability exercised during visuospatial deductive reasoning (Knauff, 2009; Tversky, 2005) supports both reading and mathematical ability by improving conceptual understanding and automaticity of word/number to visual mapping (Bower & Morrow, 1990; Chinnappan, 1998; Glenberg et al., 1987; Gogus, 2013; Greca & Moreira, 2000; Halford, 2014; McNamara et al., 1991); however, the developmental relationship between these abilities has not been tested. The current study addressed this question and tested the theoretical model in Figure 1 by utilizing the British Cohort Study (BCS) to examine the longitudinal relationship between gross and fine motor skills in infancy (22 months of age) and early childhood (42 months of age) and visuospatial deductive reasoning in adolescence (at 10 and 16 years of age). We hypothesized that both infancy and early childhood gross and fine motor skills would predict future visuospatial deductive reasoning and planned to test for the developmental specificity of this connection (i.e., testing whether motor skills during early childhood predicted significant unique variance in future reasoning when controlling for motor skills in infancy). Positive evidence for this connection would expand the developmental cascade theory to include a motor-reasoning cascade, which would also support mental model theory by expanding our understanding of the developmental trajectory of the relationship between motor skills and deductive reasoning. In addition, we hypothesized that the association between early motor skills and adolescent deductive reasoning may statistically mediate the well-documented relationship between early motor skills and adolescent math and reading performance—this finding could illuminate a potential mechanism (i.e., mental modeling ability) by which early motor skills might initiate future development in distant cognitive domains such as math and reading. Understanding this facet of development will help inform and highlight the

importance of early intervention programs aimed at facilitating motor development in children.

Method

Data and Sample

Data were drawn from the BCS, a nationally representative study of 17,196 children born in the United Kingdom in 1970 (University of London, Institute of Education, Centre for Longitudinal Studies, 2016). Data were collected and children were assessed at subsequent waves using a battery of cognitive, behavioral, and medical tests. Although the 1970 BCS is still actively collecting data, the present study only utilized the waves of data collected in 1972 (22 months of age; infancy), in 1974 (42 months of age; early childhood), in 1980 (10 years of age; Adolescence 1), and in 1986 (16 years of age; Adolescence 2). The sample size varies at each wave and for each analysis (ranging from 264 to 1,373 participants; for our analysis, $N = 1,233$; 95% British, 5% other race/ethnicity; 54% male, 46% female; 7% low income, 80% middle income, 12% high income). No survey weights were created for use in the BCS. Further description of the data set can be found in Butler et al. (1997) and Duncan et al. (2007), and normative and descriptive data for all of the measures can be found at this web page: <http://nesstar.ukdataservice.ac.uk/webview/index.jsp?v=2>. Data and study materials for all experiments are available from the U.K. Data Service (<https://ukdataservice.ac.uk/>). This study was not preregistered. This study (Protocol 2011-151; title: “A cognitive neuroscientific investigation of reasoning and creativity”) was approved by the Georgetown University Institutional Review Board.

Measures

Fine Motor Skills

Fine motor skills were measured with a design copying drawing task, in which children were required to draw three basic designs: a circle, a vertical line, and a cross. This test is used extensively to assess fine motor control (Davie et al., 1972; Grissmer et al., 2010; Rutter et al., 1970). Each item was scored by an experimenter as a 1/0 binary (1 if the design was drawn correctly, 0 if scribbled or any other drawing). Because some participants did not complete all three items (due to missing data), fine motor scores were calculated as an average of all three items. This task was administered identically at the 22-month and 42-month waves.

Gross Motor Skills

Gross motor skills were measured at 22 months with four tasks, including requiring children to walk 10 steps on their own, walk holding furniture, balance on one foot, and jump in place. Each item was scored by an experimenter as a 1/0 binary (1 if they could complete the task, 0 if not). Because some participants did not complete all four tests (due to missing data), gross motor scores were calculated as an average of all four tests. At 42 months, gross motor skills were measured slightly differently: one task measuring the average amount of time a child could

balance on one foot (ranging from 1 to 6 s) across two attempts and another task measuring whether the child could jump in place (1/0 binary). These two measures were combined by dividing the amount of time spent balancing by 6, adding it to the 1/0 binary score for jumping in place, and dividing the result by 2 to create the final gross motor score.

Visuospatial Deductive Reasoning

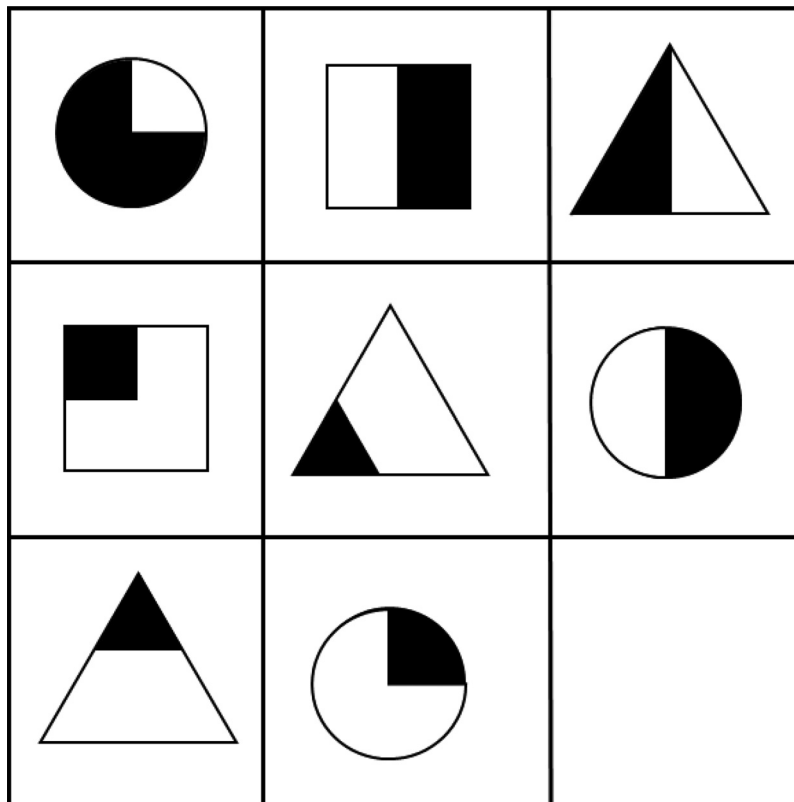
Visuospatial deductive reasoning was measured using the British Ability Scale (BAS) Matrices task, which is a visuospatial deductive reasoning task that presents participants with a series of progressively difficult matrix reasoning problems composed of several visuospatial objects, in which participants were required to select the answer choice that indicates the correct next object in the sequence (Elliott & Tyler, 1986; Figure 2). This task is comparable in nature to standard measures of visuospatial intelligence/IQ, such as Raven's Progressive Matrices (RPM; Raven, 2000) and the Wechsler Intelligence Scale for Children (Wechsler, 2008). The BAS Matrices task has been shown to correlate with these measures as well as other commonly used intelligence scales (McCallum & Karnes, 1987). Although the RPM and BAS are frequently used as measures of

“fluid intelligence,” a large body of evidence has demonstrated that visuospatial reasoning contributes significantly to performance on these tasks (Chen et al., 2017; Waschl et al., 2017), and many theories of intelligence suggest that the primary cognitive process engaged by these tasks is in fact visuospatial reasoning (Chen et al., 2017; Prabhakaran et al., 1997; Stephenson & Halpern, 2013; Tversky, 2005; Waschl et al., 2017). Conceptually, the stimuli in both RPM and BAS consist of visuospatial symbols, with the first two rows being analogous to premises of a reasoning problem and the final row being analogous to the conclusion of a reasoning problem that participants must solve by deducing the pattern from the visuospatial stimuli (Elliott & Tyler, 1986; McCallum & Karnes, 1987; Raven, 2000). At age 10, children completed 28 items of this task (long form), and their score was their overall average accuracy; at age 16, children completed 11 items of this task (short form), and their score was their overall average accuracy.

Reading

Reading ability at age 10 was assessed with the standardized Edinburgh Reading Test (Unit, 1978). The standardized Edinburgh Reading Test is a test of word recognition, and items were

Figure 2
Visuospatial Deductive Reasoning Task



Note. The image shown below is an author-created reproduction of the stimuli from the BAS Matrices task. The full set of actual stimuli from the BAS Matrices task can be accessed on the U.K. Data Service (http://doc.ukdataservice.ac.uk/doc/8288/mrdoc/pdf/bcs70_1986_reading_and_matrices_tests_data_note.pdf).

carefully selected to cover a wide age range of ability from 7 to 13 years in a form suitable to straddle the 10-year cohort. The test contained 67 items that examined vocabulary, syntax, sequencing, comprehension, and retention. The final reading score was their overall accuracy on the standardized Edinburgh Reading Test (hereafter called Reading_{10years}).

Math

Math ability at age 10 was assessed with the Friendly Maths Test, which was developed by BCS researchers and collaborators who specialized in mathematics instruction (Butler et al., 1997; University of London, Institute of Education, Centre for Longitudinal Studies, 2016). This measure was piloted in Bristol schools each on 400 children before administration in the actual study. The Friendly Maths Test consisted of a total of 72 multiple choice questions and covered the primary rules of arithmetic: number skills, fractions, measures in a variety of forms, algebra, geometry, and statistics. The final math score was their overall accuracy on the Friendly Maths Test (hereafter called Math_{10years}).

Income and Class

Gross weekly family income was collected at 10 years of age, in the form of a 6-point scale with the following brackets: under £35, £35–£49, £50–£99, £100–£149, £150–£199, £200–£249, and £250+. Income data were not collected at the 16-year data point. Social class was collected at 42 months, in the form of a 6-point scale with the following brackets: Social Class I, Social Class II, Social Class IIINM, Social Class IIIM, Social Class IV, and Social Class V. This British system of decreasing social class (where Social Class I represents the elite class) roughly maps onto the different income brackets (Giddens, 1972), though the class variable is descending and the income variable is ascending.

Gender

Gender of the children was recorded as binary (0 = female, 1 = male) at 42 months. This variable is assumed not to have changed across all data points.

Analyses

All analyses were conducted in Stata I/C 16.0 (Hamilton, 2012). We first ran baseline correlations to examine the relationship between motor skills in infancy and early childhood, as well as the relationship between reasoning at 10 years and reasoning at 16 years. Our primary analyses included the following eight ordinary least squares (OLS) regression models listed below, which tested for relationships between fine and gross motor abilities during infancy and early childhood and reasoning at 10 and 16 years (adolescence), controlling for gender, income at 10 years, and class during early childhood. Due to missing data for different variables, each model included different sample sizes (shown below each model). All models used robust standard errors. All models were run first as OLS regressions and then as Poisson models to account for the nonnormal, count nature of the dependent variables; results were virtually identical across specifications, so OLS was used for final analysis.

$$Y_{Reason_10years} = \beta_0 + \beta_1 FM_Infancy_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 978)$$

$$Y_{Reason_16years} = \beta_0 + \beta_1 FM_Infancy_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 260)$$

$$Y_{Reason_10years} = \beta_0 + \beta_1 FM_EarlyChild_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 1,233)$$

$$Y_{Reason_16years} = \beta_0 + \beta_1 FM_EarlyChild_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 323)$$

$$Y_{Reason_10years} = \beta_0 + \beta_1 GM_Infancy_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 962)$$

$$Y_{Reason_16years} = \beta_0 + \beta_1 GM_Infancy_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 249)$$

$$Y_{Reason_10years} = \beta_0 + \beta_1 GM_EarlyChild_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 784)$$

$$Y_{Reason_16years} = \beta_0 + \beta_1 GM_EarlyChild_i + \beta_2 Gender_i + \beta_3 Income_10years_i + \beta_4 Class_EarlyChild_i + \varepsilon_i (N = 219)$$

Additional regression and sensitivity analyses were run in Stata. Mediation analyses were conducted with structural equation modeling in Stata, using bootstrapped confidence intervals set to 95% confidence level with 500 Monte Carlo draws, and indirect effects were estimated with ACME (Shrout & Bolger, 2002).

Table 1
Descriptive Statistics for All Variables

Variable	Range	<i>M</i>	<i>SD</i>
FM_Infancy	0–1	0.21	0.26
FM_EarlyChild	0–1	0.44	0.32
GM_Infancy	0–1	0.85	0.22
GM_EarlyChild	0–1	0.75	0.18
Reasoning_10years	0–100%	55.34%	18.96%
Reasoning_16years	0–100%	80.57%	15.14%
Reading_10years	0–100%	60.04%	18.91%
Math_10years	0–100%	61.04%	17.11%
Class_EarlyChild	1–6	3.61	1.20
Income_10years	1–6	3.01	1.27
Gender	46.4% female, 53.6% male		

Note. FM_Infancy = fine motor skills at 22 months of age; FM_EarlyChild = fine motor skills at 42 months of age; GM_Infancy = gross motor skills at 22 months of age; GM_EarlyChild = fine motor skills at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; Reading_10years = reading performance on the standardized Edinburgh Reading Test at 10 years of age; Math_10years = math performance on the Friendly Maths Test at 10 years of age; Class_EarlyChild = social class at 42 months of age; Income_10years = gross weekly family income at 10 years of age. Gender: 0 = female, 1 = male.

Results

Correlations Among Primary Measures

Descriptive statistics for all variables can be found in Table 1. Correlations between all primary measures can be found in Table 2.

Regression Results

Fine motor skills during infancy significantly positively predicted reasoning ability at 10 years of age but did not significantly predict reasoning ability at 16 years of age (see Table 3). Fine motor skills during early childhood significantly positively predicted reasoning ability at both 10 years of age and 16 years of age (see Table 4). A 1.0-standard-deviation increase in fine motor skills during early childhood predicted about a .21-standard-deviation increase in reasoning ability at both 10 years and 16 years of age. No significant relationship emerged between gross motor

skills during infancy or early childhood and reasoning at either 10 or 16 years of age (Tables 5 and 6).

Based on our initial findings, we ran additional regression models to test whether gross or fine motor skills predicted unique variance in reasoning ability at different ages. We ran all four of the regression models of fine motor skills on reasoning including gross motor skills at the appropriate time point:

$$Y_{Reason_10years} = \beta_0 + \beta_1 FM_Infancy_i + \beta_2 GM_Infancy_i + \beta_3 Gender_i + \beta_4 Income_10years_i + \beta_5 Class_EarlyChild_i + \epsilon_i (N = 809)$$

$$Y_{Reason_16years} = \beta_0 + \beta_1 FM_Infancy_i + \beta_2 GM_Infancy_i + \beta_3 Gender_i + \beta_4 Income_10years_i + \beta_5 Class_EarlyChild_i + \epsilon_i (N = 217)$$

$$Y_{Reason_10years} = \beta_0 + \beta_1 FM_EarlyChild_i + \beta_2 GM_EarlyChild_i + \beta_3 Gender_i + \beta_4 Income_10years_i + \beta_5 Class_EarlyChild_i + \epsilon_i (N = 778)$$

$$Y_{Reason_16years} = \beta_0 + \beta_1 FM_EarlyChild_i + \beta_2 GM_EarlyChild_i + \beta_3 Gender_i + \beta_4 Income_10years_i + \beta_5 Class_EarlyChild_i + \epsilon_i (N = 217)$$

Results indicate that gross motor skills did not predict reasoning in any model and that fine motor skills at infancy marginally positively predicted reasoning ability at 10 years and remained non-significant at 16 years of age (Tables 7 and 8). Fine motor skills during early childhood, however, still significantly positively predicted reasoning at 10 years of age and 16 years of age, even when controlling for gross motor abilities during early childhood (see Table 8).

Table 2
Correlation Matrix for Primary Measures

Variable	1	2	3	4	5	6	7
1. FM_Infancy	—						
2. FM_EarlyChild	.15***	—					
3. GM_Infancy	.09***	.08***	—				
4. GM_EarlyChild	.01	.10***	.08*	—			
5. Reasoning_10years	.09***	.27***	.04	.04	—		
6. Reasoning_16years	.14**	.24***	-.01	-.05	.42***	—	
7. Reading_10years	.11***	.27***	.06*	.02	.59***	.38***	—
8. Math_10years	.13***	.25***	.04	.03	.63***	.41***	.75***

Note. FM_Infancy = fine motor skills at 22 months of age; FM_EarlyChild = fine motor skills at 42 months of age; GM_Infancy = gross motor skills at 22 months of age; GM_EarlyChild = fine motor skills at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; Reading_10years = reading performance on the standardized Edinburgh Reading Test at 10 years of age; Math_10years = math performance on the Friendly Maths Test at 10 years of age.

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

This document is copyrighted by the American Psychological Association or one of its allied publishers. This article is intended solely for the personal use of the individual user and is not to be disseminated broadly.

Table 3*Results of Regression Models of Fine Motor Skills in Infancy on Reasoning at 10 and 16 Years of Age*

Variable	Reasoning_10years			Reasoning_16years		
	β	<i>rse</i>	<i>p</i>	β	<i>rse</i>	<i>p</i>
FM_Infancy	0.064	0.024	.046	0.087	0.034	.154
Gender	-0.039	0.012	.205	-0.093	0.017	.131
Income_10years	0.134	0.005	<.001	0.151	0.007	.016
Class_EarlyChild	-0.165	0.005	<.001	-0.056	0.008	.421

Note. FM_Infancy = fine motor skills at 22 months of age; Income_10years = gross weekly family income at 10 years of age; Class_EarlyChild = social class at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; *rse* = residual standard error. Gender: 0 = female, 1 = male.

Developmental Specificity of Fine Motor to Reasoning Cascade

Building on the previous analysis, we tested whether fine motor skills during early childhood accounted for significant unique variance in reasoning at ages 10 and 16, when controlling for fine motor skills in infancy. Across both models, fine motor skills in early childhood significantly predicted unique variance in visuospatial reasoning at 10 and 16 years of age, even when controlling for fine motor skills during infancy (Table S1).

Mediation Analyses

We further investigated whether the link between early motor skills and adolescent deductive reasoning statistically mediated the relationship between early fine motor skills and math and reading performance, established in previous empirical studies (Cameron et al., 2012; Dinehart & Manfra, 2013; Grissmer et al., 2010; Pagani & Messier, 2012; Son & Meisels, 2006). We found that fine motor skills in infancy and early childhood were significantly positively associated with both reading and math at 10 years of age (Tables S2 and S3). This established Path C (fine motor to reading and math) in our mediation models (Figures 3 and 4), and Path A (fine motor to reasoning) was established in the Regression Results section (Tables 3 and 4). To establish Path B (reasoning to reading and math), we examined whether reasoning at 10 years of age was associated with math and reading at 10 years of age when controlling for fine motor skills, gender, and income at 10 years and class in early childhood. We found significant positive associations between reasoning and both math and reading in all models (Tables S4 and S5).

Table 4*Results of Regression Models of Fine Motor Skills in Early Childhood on Reasoning at 10 and 16 Years of Age*

Variable	Reasoning_10years			Reasoning_16years		
	β	<i>rse</i>	<i>p</i>	β	<i>rse</i>	<i>p</i>
FM_EarlyChild	0.206	0.016	<.001	0.219	0.029	<.001
Gender	-0.011	0.011	.677	-0.055	0.016	.312
Income_10years	0.159	0.004	<.001	1.04	0.007	.072
Class_EarlyChild	-0.147	0.004	<.001	-0.045	0.007	.478

Note. FM_EarlyChild = fine motor skills at 42 months of age; Income_10years = gross weekly family income at 10 years of age;; Class_EarlyChild = social class at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; *rse* = residual standard error. Gender: 0 = female, 1 = male.

Finally, we tested whether the association between fine motor skills during infancy and visuospatial deductive reasoning at 10 years of age statistically mediated the association between fine motor skills during infancy and reading and math at 10 years of age. In addition, we tested whether the association between fine motor skills during early childhood and visuospatial deductive reasoning at 10 years of age statistically mediated the association between fine motor skills during early childhood and reading (see Figure 3) and math (see Figure 4) at 10 years of age. All models controlled for gender, income at 10 years, and class at 42 months.

Results showed that the links between fine motor skills during infancy with both math and reading scores were significantly mediated by adolescent reasoning (indirect effects of reasoning: Reading_10years: $z = 1.99$, $p = .046$; Math_10years: $z = 2.3$, $p = .01$). In addition, the links between fine motor skills during early childhood with both math and reading scores were also significantly mediated by adolescent reasoning (Reading_10years: $z = 8.61$, $p < .001$; see Figure 3; Math_10years: $z = 8.35$, $p < .001$; see Figure 4). All mediations were partial in nature as the direct effect was still significant; however, at least 50% of the total effect was accounted for by the link between early fine motor skills and reasoning in all four models.

See the [online supplemental materials](#) for additional results. These additional results include the following: interaction with class, interaction with gender, strength of effects, sensitivity analysis, and analyses verifying the continuous nature of the class and income variables.

Discussion

The present study provides initial evidence for a developmental cascade between fine motor skills in early childhood and visuospatial

Table 5*Results of Regression Models of Gross Motor Skills in Infancy on Reasoning at 10 and 16 Years of Age*

Variable	Reasoning_10years			Reasoning_16years		
	β	<i>rse</i>	<i>p</i>	β	<i>rse</i>	<i>p</i>
GM_Infancy	0.052	0.029	.114	0.048	0.049	.503
Gender	-0.08	0.012	.010	-0.056	0.018	.374
Income_10years	0.147	0.005	<.001	0.116	0.008	.087
Class_EarlyChild	-0.158	0.005	<.001	-0.044	0.008	.528

Note. GM_Infancy = gross motor skills at 22 months of age; Income_10years = gross weekly family income at 10 years of age; Class_EarlyChild = social class at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; *rse* = residual standard error. Gender: 0 = female, 1 = male.

deductive reasoning in late childhood and adolescence. Specifically, we found that fine motor skills during early childhood significantly positively predicted reasoning in adolescence (at both 10 and 16 years of age), even when controlling for gender and income and for gross motor skills. In addition, fine motor skills during infancy significantly positively predicted reasoning at 10 years of age but not 16 years of age. Building on prior work demonstrating the link between early motor skills and enhanced cognitive abilities in adolescence (Cameron et al., 2012; Dinehart & Manfra, 2013; Grissmer et al., 2010; Pagani & Messier, 2012; Son & Meisels, 2006), the current results demonstrate that early fine motor skills are also related to a distant domain of cognition during adolescence: visuospatial deductive reasoning. Critically, we found that fine motor skills during early childhood showed stronger and longer-lasting effects on reasoning than fine motor skills during infancy. In fact, fine motor skills during early childhood predicted unique variance in reasoning at ages 10 and 16 even when controlling for fine motor skills during infancy. This suggests that fine motor skills by early childhood are more important in predicting reasoning than skills by infancy, likely indicating that the period between infancy and early childhood is a crucial time for fine motor development with respect to future reasoning ability.

Furthermore, our findings are consistent with mental model theory, which proposes that deductive reasoning is supported by spatial cognition (Johnson-Laird, 1980, 2004, 2010). Spatial cognition causally depends on the use and development of motor skills (Ozel et al., 2004; Voyer & Jansen, 2017; Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998), and all three of these processes (reasoning, spatial cognition, and motor skills) share common neural substrates in the premotor cortex, parietal cortex, and cerebellum (Cona & Scarpazza, 2019; Eslinger et al., 2009;

Goel et al., 1998; Guell et al., 2018; Prabhakaran et al., 1997; Rizolatti & Luppino, 2001; Rowe et al., 2002; Wertheim & Ragni, 2018; Wise et al., 1997). Based on this evidence, we had hypothesized that early fine motor skills might support the development of reasoning in adolescence as the development of these skills might facilitate more fine-tuned spatial mapping during mental model construction in reasoning, which would allow for improved performance. The present results directly support that hypothesis and provide further support for mental model theory by providing a developmental framework for the connection between early fine motor skills and adolescent reasoning.

Critically, these findings provide new evidence that the link between early fine motor skills and visuospatial deductive reasoning in adolescence statistically mediates the previously established connection between early fine motor skills and both reading and math ability—accounting for over 50% of the effect. The previously established connection between early fine motor skills and later academic achievement in reading and math (Cameron et al., 2012; Dinehart & Manfra, 2013; Grissmer et al., 2010; Pagani & Messier, 2012; Son & Meisels, 2006) has been theorized to be bridged by visuospatial processing as development of fine motor skills could facilitate the acquisition of spatially based representation competencies (i.e., mental modeling ability) in math and reading (Cameron et al., 2016; Grissmer et al., 2010; Son & Meisels, 2006). Specifically, improved mental modeling ability in the context of math and reading could lead to better conceptual understanding and automaticity of word/number to visual mapping (Bower & Morrow, 1990; Cameron et al., 2016; Chinnappan, 1998; Glenberg et al., 1987; Gogus, 2013; Greca & Moreira, 2000; Grissmer et al., 2010; Halford, 2014; McNamara et al., 1991; Son & Meisels, 2006). The present study

Table 6*Results of Regression Models of Gross Motor Skills in Early Childhood on Reasoning at 10 and 16 Years of Age*

Variable	Reasoning_10years			Reasoning_16years		
	β	<i>rse</i>	<i>p</i>	β	<i>rse</i>	<i>p</i>
GM_EarlyChild	0.036	0.036	.307	-0.068	0.043	.231
Gender	-0.049	0.012	.144	0.002	0.019	.981
Income_10years	0.171	0.006	<.001	0.043	0.008	.550
Class_EarlyChild	-0.157	0.005	<.001	-0.122	0.009	.162

Note. GM_EarlyChild = fine motor skills at 42 months of age; Income_10years = gross weekly family income at 10 years of age; Class_EarlyChild = social class at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; *rse* = residual standard error. Gender: 0 = female, 1 = male.

Table 7*Results of Regression Models of Fine and Gross Motor Skills in Infancy on Reasoning at 10 and 16 Years of Age*

Variable	Reasoning_10years			Reasoning_16years		
	β	<i>rse</i>	<i>p</i>	β	<i>rse</i>	<i>p</i>
FM_Infancy	0.069	0.026	.054	0.052	0.037	.449
GM_Infancy	0.012	0.031	.734	0.061	0.048	.378
Gender	-0.061	0.013	.074	-0.067	0.019	.326
Income_10years	0.131	0.006	<.001	0.161	0.008	.020
Class_EarlyChild	-0.161	0.005	<.001	-0.049	0.009	.509

Note. FM_Infancy = fine motor skills at 22 months of age; GM_Infancy = gross motor skills at 22 months of age; Income_10years = gross weekly family income at 10 years of age; Class_EarlyChild = social class at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; *rse* = residual standard error. Gender: 0 = female, 1 = male.

is the first to directly test this hypothesis and the theoretical model in Figure 1. We found initial evidence that visuospatial deductive reasoning (i.e., mental modeling ability) could be a potential mechanism for the motor-cognitive developmental cascade between early fine motor skills and reading and math during adolescence. It is important to note, however, that no causal conclusions can be made based on the results of our mediation analysis. These results demonstrate the need for researchers to measure reasoning ability (in both visuospatial and verbal domains) in future longitudinal studies of child development as this will allow for further examination of the development of this understudied ability and how the development of reasoning may support other developmental cascades.

An important limitation of this study is that we did not have measures of spatial cognition. It is conceivable that spatial cognition in middle childhood mediates early childhood fine motor skills and visuospatial deductive reasoning, but it is also possible that fine motor skills transfer directly to reasoning. Another limitation is that we lacked a measure of verbal deductive reasoning during adolescence—a developmental connection between fine motor skills and verbal deductive reasoning would demonstrate even further transfer between skills (i.e., fine motor skills in tracing shapes predict not only reasoning about visuospatial shapes but also reasoning about completely verbal, nonspatial stimuli). In addition, much of mental model literature is based upon verbal deductive reasoning (Johnson-Laird, 1980, 2004, 2010). Last, the BCS did not include any neural measurement to determine

which brain resources might subserve the developmental connection between fine motor skills and reasoning. Future research should add measures of spatial cognition, verbal deductive reasoning, and neuroimaging to test connections between fine motor skills and reasoning.

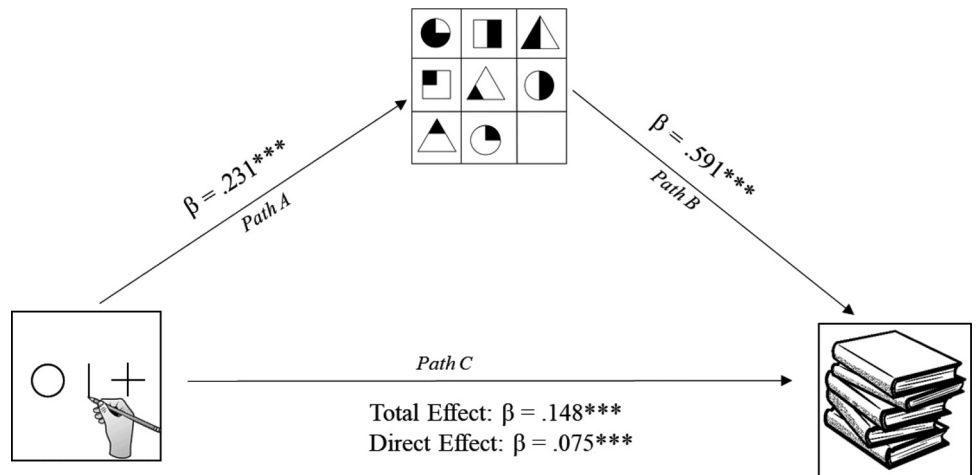
Notably, we did not find evidence that gross motor skills predicted reasoning during adolescence, despite hypothesizing that the differentiation between allocentric and egocentric spatial processing facilitated by gross motor development might support spatialization of abstract concepts in reasoning. One possible explanation is that the gross motor skills task included in the current data set (collected in the 1970s) was not as sensitive as modern measures of gross motor skills. Namely, all of the items were scored on a 1/0 basis for correct or incorrect, whereas modern tasks facilitate continuous measurement of different levels of performance (i.e., 0 to 5). This limitation also applies to the fine motor task, administered via pencil and paper in the current study—this measure could be made more sensitive using modern methods, such as the tracing tasks administered via touch screen tablets (Flatters et al., 2014; Giles et al., 2018). Alternatively, it is possible that fine motor skills share a unique connection to visuospatial deductive reasoning that gross motor skills do not. Last, it is possible that the developmental relationships observed in the present study and data set could be cohort specific to children growing up in the 1970s. It is conceivable that modern technological advances and changes in children's average physical activity could change the developmental trajectory between early motor skills and adolescent reasoning ability, perhaps advancing or delaying the connection or

Table 8*Results of Regression Models of Fine and Gross Motor Skills in Early Childhood on Reasoning at 10 and 16 Years of Age*

Variable	Reasoning_10years			Reasoning_16years		
	β	<i>rse</i>	<i>p</i>	β	<i>rse</i>	<i>p</i>
FM_EarlyChild	0.253	0.019	<.001	0.203	0.037	.010
GM_EarlyChild	0.019	0.035	.575	-0.052	0.044	.365
Gender	-0.025	0.012	.446	0.002	0.019	.979
Income_10years	0.163	0.005	<.001	0.05	0.008	.457
Class_EarlyChild	-0.139	0.005	<.001	-0.096	0.011	.281

Note. FM_EarlyChild = fine motor skills at 42 months of age; GM_EarlyChild = fine motor skills at 42 months of age; Income_10years = gross weekly family income at 10 years of age; Class_EarlyChild = social class at 42 months of age; Reasoning_10years = visuospatial reasoning performance on the BAS Matrices task at 10 years of age; Reasoning_16years = visuospatial reasoning performance on the BAS Matrices task at 16 years of age; *rse* = residual standard error. Gender: 0 = female, 1 = male.

Figure 3
Visuospatial Deductive Reasoning Mediates the Link Between Early Childhood Fine Motor Skills and Reading at 10 Years of Age



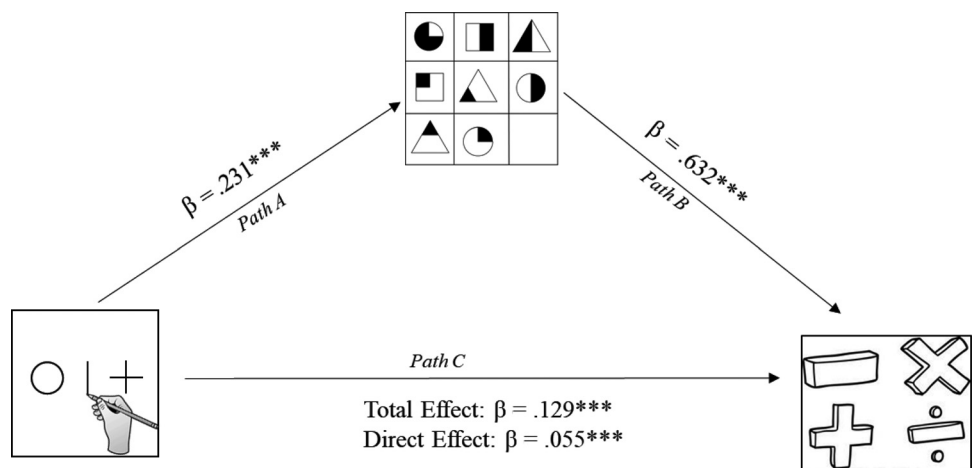
Note. The images shown below (besides the author-created reproduction of the BAS Matrices stimuli shown in the upper portion of the figure) were obtained from the public domain and can be accessed at publicdomainvectors.org. The full set of actual stimuli from the BAS Matrices task can be accessed on the U.K. Data Service (http://doc.ukdataservice.ac.uk/doc/8288/mrdoc/pdf/bcs70_1986_reading_and_matrices_tests_data_note.pdf).
 *** $p < .001$.

eliminating it entirely. Future research should examine whether the results of the present study can be replicated in later cohorts.

Despite these limitations and outstanding questions, the present findings have broader implications for the field of early motor intervention. Motor development is closely monitored and intervened upon during infancy and early adulthood

(Mahoney et al., 2004). Although these intervention programs are typically motivated by their ability to improve children's long-term motor outcomes, the present findings demonstrate that these early intervention programs may also yield benefits in adolescent visuospatial deductive reasoning. Furthermore, the present findings indicate a potential mechanism (i.e., mental

Figure 4
Visuospatial Deductive Reasoning Mediates the Link Between Early Childhood Fine Motor Skills and Math at 10 Years of Age



Note. The images shown below (besides the author-created reproduction of the BAS Matrices stimuli shown in the upper portion of the figure) were obtained from the public domain and can be accessed at publicdomainvectors.org. The full set of actual stimuli from the BAS Matrices task can be accessed on the U.K. Data Service (http://doc.ukdataservice.ac.uk/doc/8288/mrdoc/pdf/bcs70_1986_reading_and_matrices_tests_data_note.pdf).
 *** $p < .001$.

modeling ability) that would explain why early motor intervention programs have been linked to improvements in math and reading outcomes. Overall, the present study and its findings highlight the importance of early motor intervention programs and contextualize the impact of those interventions on later cognitive and academic skills.

References

- Adolph, K. E., & Berger, S. E. (2007). Motor development. In W. Damon & R. M. Lerner (Eds.), *Handbook of child psychology* (pp. 113–157). Wiley. <https://doi.org/10.1002/9780470147658.chpsy0204>
- Adolph, K. E., & Tamis-LeMonda, C. S. (2014). The costs and benefits of development: The transition from crawling to walking. *Child Development Perspectives*, 8(4), 187–192. <https://doi.org/10.1111/cdep.12085>
- Bornstein, M. H., Hahn, C.-S., & Suwalsky, J. T. D. (2013). Physically developed and exploratory young infants contribute to their own long-term academic achievement. *Psychological Science*, 24(10), 1906–1917. <https://doi.org/10.1177/0956797613479974>
- Bower, G. H., & Morrow, D. G. (1990). Mental models in narrative comprehension. *Science*, 247(4938), 44–48. <https://doi.org/10.1126/science.2403694>
- Butler, N., & Bynner, J. M., & University of London, Institute of Education, Centre for Longitudinal Studies. (1997). *1970 British Cohort Study: Ten-year follow-up, 1980*. U.K. Data Service. <https://doi.org/10.5255/UKDA-SN-3723-7>
- Cameron, C. E., Brock, L. L., Murrah, W. M., Bell, L. H., Worzalla, S. L., Grissmer, D., & Morrison, F. J. (2012). Fine motor skills and executive function both contribute to kindergarten achievement. *Child Development*, 83(4), 1229–1244. <https://doi.org/10.1111/j.1467-8624.2012.01768.x>
- Cameron, C. E., Cottone, E. A., Murrah, W. M., & Grissmer, D. W. (2016). How are motor skills linked to children's school performance and academic achievement? *Child Development Perspectives*, 10(2), 93–98. <https://doi.org/10.1111/cdep.12168>
- Chen, Z., De Beuckelaer, A., Wang, X., & Liu, J. (2017). Distinct neural substrates of visuospatial and verbal-analytic reasoning as assessed by Raven's Advanced Progressive Matrices. *Scientific Reports*, 7(1), Article 16230. <https://doi.org/10.1038/s41598-017-16437-8>
- Chinnappan, M. (1998). Schemas and mental models in geometry problem solving. *Educational Studies in Mathematics*, 36(3), 201–217. <https://doi.org/10.1023/A:1003134323371>
- Cona, G., & Scarpazza, C. (2019). Where is the “where” in the brain? A meta-analysis of neuroimaging studies on spatial cognition. *Human Brain Mapping*, 40(6), 1867–1886. <https://doi.org/10.1002/hbm.24496>
- Davie, R., Butler, N., & Goldstein, H. (1972). *From birth to seven: The second report of the Child Development Study (1958 cohort)*. Longman.
- Dinehart, L., & Manfra, L. (2013). Associations between low-income children's fine motor skills in preschool and academic performance in second grade. *Early Education and Development*, 24(2), 138–161. <https://doi.org/10.1080/10409289.2011.636729>
- Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, 43(6), 1428–1446. <https://doi.org/10.1037/0012-1649.43.6.1428>
- Elliott, C. D., & Tyler, S. T. (1986). British Ability Scales profiles of children with reading difficulties. *Educational and Child Psychology*, 3(2), 80–89.
- Eslinger, P. J., Blair, C., Wang, J.Li., Lipovsky, B., Realmuto, J., Baker, D., Thorne, S., Gamson, D., Zimmerman, E., Rohrer, L., & Yang, Q. X. (2009). Developmental shifts in fMRI activations during visuospatial relational reasoning. *Brain and Cognition*, 69(1), 1–10. <https://doi.org/10.1016/j.bandc.2008.04.010>
- Flatters, I., Mushtaq, F., Hill, L. J. B., Holt, R. J., Wilkie, R. M., & Mon-Williams, M. (2014). The relationship between a child's postural stability and manual dexterity. *Experimental Brain Research*, 232(9), 2907–2917. <https://doi.org/10.1007/s00221-014-3947-4>
- Forgeard, M., Winner, E., Norton, A., & Schlaug, G. (2008). Practicing a musical instrument in childhood is associated with enhanced verbal ability and nonverbal reasoning. *PLoS ONE*, 3(10), Article e3566. <https://doi.org/10.1371/journal.pone.0003566>
- Frick, A., Daum, M. M., Walser, S., & Mast, F. W. (2009). Motor processes in children's mental rotation. *Journal of Cognition and Development*, 10(1-2), 18–40. <https://doi.org/10.1080/15248370902966719>
- Frick, A., & Möhring, W. (2013). Mental object rotation and motor development in 8- and 10-month-old infants. *Journal of Experimental Child Psychology*, 115(4), 708–720. <https://doi.org/10.1016/j.jecp.2013.04.001>
- Frick, A., & Möhring, W. (2015). A matter of balance: Motor control is related to children's spatial and proportional reasoning skills. *Frontiers in Psychology*, 6, Article 2049. <https://doi.org/10.3389/fpsyg.2015.02049>
- Friedman, A. H., Watamura, S. E., & Robertson, S. S. (2005). Movement-attention coupling in infancy and attention problems in childhood. *Developmental Medicine & Child Neurology*, 47(10), 660–665. <https://doi.org/10.1017/S0012162205001350>
- Funk, M., Brugger, P., & Wilkening, F. (2005). Motor processes in children's imagery: The case of mental rotation of hands. *Developmental Science*, 8(5), 402–408. <https://doi.org/10.1111/j.1467-7687.2005.00428.x>
- Galati, G., Lobel, E., Vallar, G., Berthoz, A., Pizzamiglio, L., & Le Bihan, D. (2000). The neural basis of egocentric and allocentric coding of space in humans: A functional magnetic resonance study. *Experimental Brain Research*, 133(2), 156–164. <https://doi.org/10.1007/s002210000375>
- Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, 39(1), 1–42. <https://doi.org/10.1146/annurev.ps.39.020188.000245>
- Giddens, A. (1972). Elites in the British class structure. *The Sociological Review*, 20(3), 345–372. <https://doi.org/10.1111/j.1467-954X.1972.tb00214.x>
- Giles, O. T., Shire, K. A., Hill, L. J. B., Mushtaq, F., Waterman, A., Holt, R. J., Culmer, P. R., Williams, J. H. G., Wilkie, R. M., & Mon-Williams, M. (2018). Hitting the target: Mathematical attainment in children is related to interceptive-timing ability. *Psychological Science*, 29(8), 1334–1345. <https://doi.org/10.1177/0956797618772502>
- Glenberg, A. M., Meyer, M., & Lindem, K. (1987). Mental models contribute to foregrounding during text comprehension. *Journal of Memory and Language*, 26(1), 69–83. [https://doi.org/10.1016/0749-596X\(87\)90063-5](https://doi.org/10.1016/0749-596X(87)90063-5)
- Goel, V., Buchel, C., Frith, C., & Dolan, R. J. (2000). Dissociation of mechanisms underlying syllogistic reasoning. *NeuroImage*, 12(5), 504–514. <https://doi.org/10.1006/nimg.2000.0636>
- Goel, V., Gold, B., Kapur, S., & Houle, S. (1998). Neuroanatomical correlates of human reasoning. *Journal of Cognitive Neuroscience*, 10(3), 293–302. <https://doi.org/10.1162/089892998562744>
- Gogus, A. (2013). Evaluating mental models in mathematics: A comparison of methods. *Educational Technology Research and Development*, 61(2), 171–195. <https://doi.org/10.1007/s11423-012-9281-2>
- Goodway, J., Ozmun, J., & Gallahue, D. (2019). *Understanding motor development: Infants, children, adolescents, adults* (8th ed.). Jones & Bartlett Learning.
- Greca, I. M., & Moreira, M. A. (2000). Mental models, conceptual models, and modelling. *International Journal of Science Education*, 22(1), 1–11. <https://doi.org/10.1080/095006900289976>
- Grissmer, D., Grimm, K. J., Aiyer, S. M., Murrah, W. M., & Steele, J. S. (2010). Fine motor skills and early comprehension of the world: Two new school readiness indicators. *Developmental Psychology*, 46(5), 1008–1017. <https://doi.org/10.1037/a0020104>

- Guell, X., Schmahmann, J. D., Gabrieli, J., & Ghosh, S. S. (2018). Functional gradients of the cerebellum. *eLife*, 7, Article e36652. <https://doi.org/10.7554/eLife.36652>
- Halford, G. S. (2014). *Children's understanding: The development of mental models*. Psychology Press. <https://doi.org/10.4324/9781315801803>
- Hamilton, L. C. (2012). *Statistics with Stata: Version 12*. Cengage Learning.
- Hart, R. A., & Moore, G. T. (1973). The development of spatial cognition: A review. In R. M. Downs & D. Stea (Eds.), *Image & environment: Cognitive mapping and spatial behavior* (pp. 246–288). AldineTransaction.
- Iani, F. (2019). Embodied memories: Reviewing the role of the body in memory processes. *Psychonomic Bulletin & Review*, 26(6), 1747–1766. <https://doi.org/10.3758/s13423-019-01674-x>
- Jansen, P., & Heil, M. (2010). The relation between motor development and mental rotation ability in 5- to 6-year-old children. *European Journal of Developmental Science*, 4(1), 67–75. <https://doi.org/10.3233/DEV-2010-4105>
- Johnson-Laird, P. N. (1980). Mental models in cognitive science. *Cognitive Science*, 4(1), 71–115. https://doi.org/10.1207/s15516709cog0401_4
- Johnson-Laird, P. N. (2004). The history of mental models. In K. Manktelow & M. C. Chung (Eds.), *Psychology of reasoning* (pp. 189–222). Psychology Press. <https://doi.org/10.4324/9780203506936-10>
- Johnson-Laird, P. N. (2010). Mental models and human reasoning. *Proceedings of the National Academy of Sciences of the United States of America*, 107(43), 18243–18250. <https://doi.org/10.1073/pnas.1012933107>
- Johnson-Laird, P. N., Goodwin, G. P., & Khemlani, S. S. (2017). Mental models and reasoning. In L. J. Ball & V. A. Thompson (Eds.), *The Routledge international handbook of thinking and reasoning* (pp. 346–365). Routledge. <https://doi.org/10.4324/9781315725697>
- Karmiloff-Smith, A. (2012). From constructivism to neuroconstructivism: The activity-dependent structuring of the human brain. In E. Martí & C. Rodríguez (Eds.), *After Piaget* (pp. 1–14). Transaction Publishers.
- Khemlani, S., & Johnson-Laird, P. N. (2012). Theories of the syllogism: A meta-analysis. *Psychological Bulletin*, 138(3), 427–457. <https://doi.org/10.1037/a0026841>
- Klatzky, R. L. (1998). Allocentric and egocentric spatial representations: Definitions, distinctions, and interconnections. In C. Freksa, C. Habel, & K. F. Wender (Eds.), *Spatial cognition: An interdisciplinary approach to representing and processing spatial knowledge* (pp. 1–17). Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-69342-4_1
- Knauff, M. (2009). A neuro-cognitive theory of deductive relational reasoning with mental models and visual images. *Spatial Cognition & Computation*, 9(2), 109–137. <https://doi.org/10.1080/13875860902887605>
- Lehmann, J., Quaiser-Pohl, C., & Jansen, P. (2014). Correlation of motor skill, mental rotation, and working memory in 3- to 6-year-old children. *European Journal of Developmental Psychology*, 11(5), 560–573. <https://doi.org/10.1080/17405629.2014.888995>
- Libertus, K., Joh, A. S., & Needham, A. W. (2016). Motor training at 3 months affects object exploration 12 months later. *Developmental Science*, 19(6), 1058–1066. <https://doi.org/10.1111/desc.12370>
- Mahoney, G., Robinson, C., & Fewell, R. R. (2001). The effects of early motor intervention on children with Down syndrome or cerebral palsy: A field-based study. *Journal of Developmental and Behavioral Pediatrics*, 22(3), 153–162. <https://doi.org/10.1097/00004703-200106000-00001>
- Mahoney, G., Robinson, C., & Perales, F. (2004). Early motor intervention: The need for new treatment paradigms. *Infants and Young Children*, 17(4), 291–300. <https://doi.org/10.1097/00001163-200410000-00003>
- McCallum, R. S., & Karnes, F. (1987). Comparison of intelligence tests. *School Psychology International*, 8(2-3), 133–139. <https://doi.org/10.1177/0143034387082009>
- McNamara, T., Miller, D. L., & Bransford, J. D. (1991). Mental models and reading comprehension. In R. Barr, M. L. Kamil, P. B. Mosenthal, & P. D. Pearson (Eds.), *Handbook of reading research* (Vol. 2, pp. 490–511). Erlbaum, Inc.
- Möhring, W., & Frick, A. (2013). Touching up mental rotation: Effects of manual experience on 6-month-old infants' mental object rotation. *Child Development*, 84(5), 1554–1565. <https://doi.org/10.1111/cdev.12065>
- Ozel, S., Larue, J., & Molinaro, C. (2004). Relation between sport and spatial imagery: Comparison of three groups of participants. *The Journal of Psychology*, 138(1), 49–63. <https://doi.org/10.3200/JRLP.138.1.49-64>
- Ozonoff, S., Young, G. S., Goldring, S., Greiss-Hess, L., Herrera, A. M., Steele, J., Macari, S., Hepburn, S., & Rogers, S. J. (2008). Gross motor development, movement abnormalities, and early identification of autism. *Journal of Autism and Developmental Disorders*, 38(4), 644–656. <https://doi.org/10.1007/s10803-007-0430-0>
- Pagani, L. S., & Messier, S. (2012). Links between motor skills and indicators of school readiness at kindergarten entry in urban disadvantaged children. *Journal of Educational and Developmental Psychology*, 2(1), 95–107. <https://doi.org/10.5539/jedp.v2n1p95>
- Piaget, J. (1952). *The origins of intelligence in children*. W. W. Norton & Co. <https://doi.org/10.1037/11494-000>
- Prabhakaran, V., Smith, J. A. L., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (1997). Neural substrates of fluid reasoning: An fMRI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive Psychology*, 33(1), 43–63. <https://doi.org/10.1006/cogp.1997.0659>
- Ragni, M., & Knauff, M. (2013). A theory and a computational model of spatial reasoning with preferred mental models. *Psychological Review*, 120(3), 561–588. <https://doi.org/10.1037/a0032460>
- Raven, J. (2000). The Raven's progressive matrices: Change and stability over culture and time. *Cognitive Psychology*, 41(1), 1–48. <https://doi.org/10.1006/cogp.1999.0735>
- Rizzolatti, G., & Luppino, G. (2001). The cortical motor system. *Neuron*, 31(6), 889–901. [https://doi.org/10.1016/S0896-6273\(01\)00423-8](https://doi.org/10.1016/S0896-6273(01)00423-8)
- Rowe, J., Friston, K., Frackowiak, R., & Passingham, R. (2002). Attention to action: Specific modulation of corticocortical interactions in humans. *NeuroImage*, 17(2), 988–998. <https://doi.org/10.1006/nimg.2002.1156>
- Rutter, M., Tizard, J., & Whitmore, K. (1970). *Education, health and behavior*. Longman Publishing Group.
- Schwarzer, G., Freitag, C., Buckel, R., & Lofruthe, A. (2013). Crawling is associated with mental rotation ability by 9-month-old infants. *Infancy*, 18(3), 432–441. <https://doi.org/10.1111/j.1532-7078.2012.00132.x>
- Shrout, P. E., & Bolger, N. (2002). Mediation in experimental and non-experimental studies: New procedures and recommendations. *Psychological Methods*, 7(4), 422–445. <https://doi.org/10.1037/1082-989X.7.4.422>
- Son, S.-H., & Meisels, S. J. (2006). The relationship of young children's motor skills to later school achievement. *Merrill-Palmer Quarterly*, 52(4), 755–778. <https://doi.org/10.1353/mpq.2006.0033>
- Stephenson, C. L., & Halpern, D. F. (2013). Improved matrix reasoning is limited to training on tasks with a visuospatial component. *Intelligence*, 41(5), 341–357. <https://doi.org/10.1016/j.intell.2013.05.006>
- Tversky, B. (2005). *Visuospatial reasoning*. Cambridge University Press.
- Unit, G. T. (1978). *Edinburgh Reading Test*. Hodder and Stoughton.
- University of London, Institute of Education, Centre for Longitudinal Studies. (2016). *1970 British Cohort Study response dataset, 1970-2012*. U.K. Data Service.
- Voyer, D., & Jansen, P. (2017). Motor expertise and performance in spatial tasks: A meta-analysis. *Human Movement Science*, 54, 110–124. <https://doi.org/10.1016/j.humov.2017.04.004>
- Waschl, N. A., Nettelbeck, T., & Burns, N. R. (2017). The role of visuospatial ability in the Raven's Progressive Matrices. *Journal of Individual Differences*, 38(4), 241–255. <https://doi.org/10.1027/1614-0001/a000241>
- Wechsler, D. (2008). *Wechsler Adult Intelligence Scale—Fourth edition (WAIS-IV)*. NCS Pearson.
- Wertheim, J., & Ragni, M. (2018). The neural correlates of relational reasoning: A meta-analysis of 47 functional magnetic resonance studies.

- Journal of Cognitive Neuroscience*, 30(11), 1734–1748. https://doi.org/10.1162/jocn_a_01311
- Wexler, M., Kosslyn, S. M., & Berthoz, A. (1998). Motor processes in mental rotation. *Cognition*, 68(1), 77–94. [https://doi.org/10.1016/S0010-0277\(98\)00032-8](https://doi.org/10.1016/S0010-0277(98)00032-8)
- Wise, S. P., Boussaoud, D., Johnson, P. B., & Caminiti, R. (1997). Premotor and parietal cortex: Corticocortical connectivity and combinatorial computations. *Annual Review of Neuroscience*, 20(1), 25–42. <https://doi.org/10.1146/annurev.neuro.20.1.25>
- Wohlschläger, A., & Wohlschläger, A. (1998). Mental and manual rotation. *Journal of Experimental Psychology: Human Perception and Performance*, 24(2), 397–412. <https://doi.org/10.1037/0096-1523.24.2.397>

Received April 7, 2021

Revision received December 21, 2021

Accepted February 1, 2022 ■

Members of Underrepresented Groups: Reviewers for Journal Manuscripts Wanted

If you are interested in reviewing manuscripts for APA journals, the APA Publications and Communications Board would like to invite your participation. Manuscript reviewers are vital to the publications process. As a reviewer, you would gain valuable experience in publishing. The P&C Board is particularly interested in encouraging members of underrepresented groups to participate more in this process.

If you are interested in reviewing manuscripts, please write APA Journals at Reviewers@apa.org. Please note the following important points:

- To be selected as a reviewer, you must have published articles in peer-reviewed journals. The experience of publishing provides a reviewer with the basis for preparing a thorough, objective review.
- To be selected, it is critical to be a regular reader of the five to six empirical journals that are most central to the area or journal for which you would like to review. Current knowledge of recently published research provides a reviewer with the knowledge base to evaluate a new submission within the context of existing research.
- To select the appropriate reviewers for each manuscript, the editor needs detailed information. Please include with your letter your vita. In the letter, please identify which APA journal(s) you are interested in, and describe your area of expertise. Be as specific as possible. For example, “social psychology” is not sufficient—you would need to specify “social cognition” or “attitude change” as well.
- Reviewing a manuscript takes time (1–4 hours per manuscript reviewed). If you are selected to review a manuscript, be prepared to invest the necessary time to evaluate the manuscript thoroughly.

APA now has an online video course that provides guidance in reviewing manuscripts. To learn more about the course and to access the video, visit <http://www.apa.org/pubs/journals/resources/review-manuscript-ce-video.aspx>.