

How Are Motor Skills Linked to Children's School Performance and Academic Achievement?

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ABSTRACT—*Children need a range of skills to transition successfully to formal schooling. In early childhood classrooms, children must master their fine and gross motor skills. In this article, we review the evidence that links motor skills to diverse school outcomes, then describe three sets of cognitive processes—motor coordination, executive function, and visuospatial skills—that are tapped by motor assessments. We then use these processes to explain how motor skills are implicated in children's self-regulation and their emergent literacy and numeracy. We conclude by encouraging theoretical and methodological approaches to clarify the mechanisms that implicate motor skills in school performance and achievement.*

KEYWORDS—*executive function; motor coordination; school readiness; visuospatial skills; visuomotor integration*

Motor skills are associated with a range of academic and behavioral skills, including decoding letters and words, solving quantitative problems, writing, and interacting effectively with peers and adults (1–3). However, researchers have not explained adequately how motor skills are linked to school performance and achievement. In this article, we summarize work on motor skills and identify three sets of underlying cognitive processes that are

tapped by common motor assessments—motor coordination, executive function (EF), and visuospatial skills. We then describe how these cognitive processes combine and interrelate to underlie complex behavior in early childhood, such as classroom self-regulation and emergent academic skills. Finally, we suggest testing cognitive theories to explain links between motor skills and school outcomes, and encourage measurement to understand the interrelated cognitive processes measured by motor assessments.

MOTOR SKILLS ARE ASSOCIATED WITH LEARNING IN EARLY CHILDHOOD

Motor skills refer to the underlying internal processes responsible for moving the body or parts of the body in space. Motor skills are not only the movements themselves, but include the cognitive processes that give rise to movements (4). Motor-related skills, including perceptual-motor, sensorimotor, and psychomotor skills, implicate sensory perception and the interaction of the movement systems (i.e., body parts) with the cognitive system (5).

Whereas gross motor skills involve the body's large muscles and pertain to balance, orientation and movement of the trunk and limbs, and posture (4), fine motor skills involve coordinating small muscle movements needed for tasks like drawing, writing, speaking, and playing an instrument (6). While they are clearly related and develop together, correlations between fine and gross motor assessments are moderate, from $r = .30$ (7) to $r = .60$ (8).

In concurrent and longitudinal studies, gross and fine motor skills are distinct in their predictive validity. Gross motor skills are a critical part of children's developing social competencies and physical well-being (9–11), and are a gateway to engagement in learning and social activities, including sports and games, throughout the school years (8, 12). In contrast, fine motor skills are associated more robustly with academic achievement. In one study (13), U.S. children with strong fine motor skills at age 5 performed more optimally than peers with weak motor skills in math and reading when they were 6, 8, and

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10 years old. Analyses controlled for a diverse set of variables, including sociodemographic characteristics, prior achievement and gross motor skills, and teacher-reported attention. Despite associations for both gross and fine motor skills with cognitive as well as social outcomes, the precise mechanisms that link motor skills to school performance are unclear.

Cognitive Processes Measured by Motor Assessments

The tasks used in motor assessments vary widely in what they require of children. Although there may be other processes, we highlight three interrelated cognitive processes that are tapped by tasks that traditionally measure motor skills: motor coordination, EF, and visuospatial skills.

Motor Coordination

Early childhood classrooms require children to coordinate their body movements in directed action, in tasks such as self-care, emergent writing, paper-pencil tasks, and manipulating objects (14). These multistep tasks require motor planning and spatial sequencing, with improvement dependent on deliberate (i.e., cognitive) choices, such as when a child decides to use smaller blocks to build a tower because they are easier to grasp (15). Children who find it easier to tie their shoes, manage classroom materials, and use pens and pencils to write have an advantage in the school setting (16). In contrast, for children who struggle with movement difficulties—including the 5–10% of children diagnosed with developmental coordination disorder—school can be challenging (8, 17). Children who are clumsy may be rejected socially or lack the confidence to participate in sports or games (12). Four- to six-year-olds with poor motor skills are more likely to have poor social skills, which in turn contribute to internalizing symptoms such as anxiety (10). Furthermore, between 4 and 6 years, children who see themselves as competent at academic and gross motor tasks tend to see themselves as competent socially ($r_s = .32-.56$; 11), illustrating the interrelatedness and complexity of domains of development often considered distinct.

Executive Function

New learning requires EF, the set of cognitive processes that helps children focus and shift their attention, manipulate information in working memory, and inhibit maladaptive responses to meet adaptive goals (7, 18). When performing motor actions, children must maintain attention to the task, whether sorting manipulatives or organizing learning materials. In concurrent analyses (1), EF processes are more important for 4-year-olds than for 5-year-olds when performing a common fine motor task called the Test of Visuo-Motor Integration (VMI; 6), suggesting that younger children need to devote more cognitive resources to this task than older children. Correlations between motor skills and EF are positive though variable in typically developing students (1, 7, 19). Thus, while distinct, EF and motor skills are also interrelated (20). This interrelation may

be especially evident near school entry, when many motor tasks are relatively new to children and require EF to master (21–23).

Visuospatial Skills

A final set of cognitive processes tapped by motor assessments is visuospatial skills, which include perceiving spatial relations, visualizing objects using cognitive representations in 2D or 3D space, and manipulating those representations (24). Many of these representational and constructional skills develop dramatically between 4 and 5 years, when most children are expected to be ready for school (25). Furthermore, among children ages 4–11, measures of visual processing and fine manual control—which include both fine motor precision and integration of perceptual information with movements—account for the stable association among latent motor and cognitive performance (26). A common integration task is design copying as in the VMI; this is a good example of a task commonly labeled fine motor that entails many complex cognitive processes, including both visual processing and visuomotor integration. Facility in copying designs is correlated with several complex cognitive processes, including the ability to judge line length, represent shapes manually, rotate visual stimuli mentally, and reproduce a figure in free space (27, 28). The comparative and planning processes involved in copying are not needed to the same extent in free-hand drawing, tracing, or building freely in 3D (25). Three-year-olds' visuospatial performance on a task involving copying a model in three dimensions explained variance in math achievement at age 4, even after controlling for EF (24). Furthermore, visuospatial skills are exceptional among those learners who later thrive in the STEM fields—science, technology, engineering, and mathematics (29).

INTERRELATED MOTOR AND COGNITIVE PROCESSES IN THE EARLY CHILDHOOD CLASSROOM

In preschool and early elementary classrooms, motor coordination, EF, and visuospatial processes do not exist in isolation; rather, they combine and interrelate with each other and with other skills to form the basis for children's successful behaviors in the learning context (8, 18). Given these connections, motor skills may be linked to achievement through many pathways: Some motor skills, such as those requiring visuospatial processing, may be involved directly in domain-specific learning, such as math. Strong motor skills may also compensate for weak behavioral or academic skills (23). Motor skills underlie school readiness in at least two areas: classroom self-regulation and emergent academic skills, namely literacy and numeracy.

Classroom Self-Regulation

School exerts many simultaneous demands on children's emerging ability to control and regulate their emotions and behaviors, including their body movements. Furthermore, children vary

widely in their readiness to meet these demands. For example, in one study (30), there was a 15-month gap in fine motor skills of the most and least competent 5-year-olds. In another study (16), children whose classroom fine motor skills were rated good by their teachers (e.g., staying within the lines while coloring, tying their shoelaces, and writing with good penmanship) had more effective attention and EF processes than children with less optimal classroom fine motor skills; and children with strong gross motor skills (e.g., organizing movements and materials effectively during seatwork) had more optimal social skills and fewer competing problem behaviors than children with poor gross motor skills. When children do not need to devote attention and energy to behavioral tasks that require their fine and gross motor skills in the classroom, they have more time to spend on other tasks and experience less frustration and social difficulties (8). Moreover, children with strong attention, self-control, and working memory may engage more readily with new tasks that require increasingly sophisticated motor expertise.

Emergent Literacy and Numeracy

Many learning tasks in early childhood are intended to prepare children to become fluent with letters and numbers. Emergent literacy encompasses children's experiences with books and reading, including nascent knowledge of how print works (e.g., letter knowledge, conventions of reading, and emergent writing) and awareness of the sounds in language. Fine motor and emergent literacy skills, including emergent writing, are distinctly related (21). The design copying aspect of fine motor skills is related positively with name writing, written expression, and math (r s ranging from .32 to .43; 3, 16, 31).

Acquiring competency in literacy and numeracy involves recognizing and eventually reproducing visual representations of higher order concepts. Furthermore, children's culture and experiences—including motor experiences—assist their acquisition of more complex and encompassing conceptual structures across domains (32). Fine motor activities may provide children the opportunity to practice mapping visual representations to concepts, such as drawing letters with markers, crayons, or pencils; counting the number of beads on a necklace; or sorting stones into groups of three.

Motor Skills as a Compensatory Process

Strong fine and visuomotor skills might compensate for other challenges to support children's self-regulation in the classroom and help them learn literacy (23) and math (33). In two studies, when visuomotor skills were strong, children's achievement did not suffer when either their relationships with teachers were compromised (33) or their inhibitory control was poor (23). Compensatory mechanisms may be particularly relevant for learning to read, which draws heavily on EF early in the process (18). In other words, before children have *cracked the code*, they must attend to various stimuli—both aural and written—while using working memory to combine information; they must also inhibit

incorrect associations among letter sounds, shapes, and meanings. If children have strong visuomotor skills, they can devote more of their limited cognitive resources to integrating conceptual rather than perceptual information. This process is likely specific to tasks that require perceptual distinctions: Even 4-year-olds with poor initial inhibitory control improved adequately in print knowledge during the school year when they had strong visuomotor skills. However, this compensatory association did not emerge for language outcomes, which suggests domain specificity in how visuomotor skills contribute to learning in academic areas that exert perceptual and motor demands. Given that math also requires perceptual and cognitive elements, fine and visuomotor skills may similarly underlie the acquisition of quantitative competencies, which are more spatially based than often recognized (24, 34). More work in this area is needed, and we next suggest two possible directions.

THEORETICAL AND METHODOLOGICAL SUGGESTIONS TO CLARIFY UNDERLYING MECHANISMS

Scholars should test theoretical models that explain links between motor skills and school readiness. For example, the theory of cognitive load assumes finite processing capacity for a given task (35). When tasks are novel or call on many resources simultaneously, learners must use executive skills associated with the prefrontal cortex (PFC) to monitor, plan, and control their actions. Then, as individuals learn and become increasingly good at the task, bilateral and PFC patterns of neural activation decrease and shift to subcortical motor areas, which are associated with less effortful processing (36). When such automaticity occurs, the cognitive resources that were originally needed to perform the novel task become available for other challenges, such as effective problem solving and higher order learning (22). With development and practice, capacity can also increase (32).

The theory of cognitive load is often tested with the dual task design, which researchers could apply more frequently during early childhood to clarify the types of motor demands that affect children's achievement and behavior (37). Dual task designs hold a motor demand (such as using a pencil) constant while varying the cognitive load (such as solving a problem) or vice versa (17); for example, a young child might be asked to solve a maze with a pencil while the size of the maze is changed to vary its difficulty. Children whose performance on the maze declines when the maze is small (e.g., those who make more errors or take more time to complete the task) exemplify how greater perceptual and motor demands affect a cognitive outcome. We also need to understand more deeply—especially for children who struggle in school—how performance changes over the short and long term on academic tasks with a motor demand, as well as how initial performance and perceived competence affect children's learning and willingness to engage in the tasks they

find challenging (11, 12). Tasks that are inconsistent (i.e., those for which requirements change over time) are harder to learn than others because of heavy cognitive load; in addition, success and feelings of self-efficacy early in the learning process contribute to final performance (22, 38). Because formal schooling presents children with constantly changing tasks that increase in complexity, applications of cognitive load and related theories (see 38) in early childhood could illuminate how children acquire motor competence and inform intervention.

Research is also needed to characterize the trajectories and associations among motor skill subcomponents and distal outcomes such as math achievement. Longitudinal designs are important in this effort, because associations may change over development; for example, basic paper–pencil coordination skills interconnect with math achievement and cognitive skills at school entry, yet over time, they become less relevant for achievement (39) even as visuomotor integration skills remain fundamental (13, 26). This pattern suggests that skills codevelop in a system, with certain lower order skills constraining the acquisition of higher order skills through their contributions to intermediate or mediating skills. In one study of 5-year-olds (39), strong paper–pencil coordination skills predicted more optimal visuomotor integration, which in turn predicted higher math achievement. In contrast, only visuomotor integration was related to math achievement among 6-year-olds; paper–pencil coordination skills were no longer associated with visuomotor integration. Neo-Piagetians describe how children develop increasingly sophisticated representations of problems by consolidating skills at lower or less integrated levels; the role of culture and experience in practicing skills is central (32). Aligned with this view, in a study of math achievement in 5-year-olds, using manipulatives (i.e., motor skills) helped learning, whereas by the time the children turned 6, teacher-led discussions about math predicted higher achievement (40). However, systematic attention to the role of motor skills in learning has become rarer in schools as academic expectations press downward into lower grades. Thus, measuring and supporting children’s motor competencies accurately becomes critical, especially because many children struggle with both gross (41) and fine motor skills (30).

Our second set of recommendations concerns methods. We encourage work that includes many measures of motor skills and controls for other cognitive skills, to disentangle which of the processes that underlie performance on motor assessments—motor coordination, EF, and visuospatial skills—are associated with particular school-related outcomes. Visuomotor integration is tied increasingly to academic achievement. However, because so few studies incorporate multiple measures of motor skills, eliminating the role of other constructs such as EF is difficult. Creating latent variables from a battery of tasks may also be effective (19, 26). Corroborating the growing number of studies suggesting the importance of visuomotor integration (2, 3, 7), another study (26) used 18 subtests to identify visual processing

and fine manual control as the two latent skills responsible for the link between cognitive and motor skills among 4- to 11-year-olds. As a complementary effort, deliberately studying the different demand characteristics (42) across the spectrum of motor tasks could help illuminate why and when a particular task contributes to various school outcomes.

We recognize a testing burden lurking under the recommendation that scholars collect numerous measures. We therefore echo Adolph’s (43) recommendations to scholars of motor development among infants, and encourage researchers to share information that may not be published, such as correlation matrices from studies with motor measures. Similarly, new analyses of existing data sources can help illuminate measures that are appropriate for a given population. For example, item-level analyses can indicate whether a measure displays adequate variability for a specific sample or subsample (44). In addition, multivariate conceptualizations of latent constructs accommodate both unique and overlapping mechanisms across distinct tasks (45). Finally, we need analyses that incorporate additional information beyond only mean levels of performance; for example, reaction time is a complementary process that gives meaningful information beyond an individual’s mean performance on a task (22).

SUMMARY

Successful behavior in the classroom is complex and requires perceptual, EF, spatial, and motor processes that interrelate and build on each other (39). In this article, we have proposed scholarship that theoretically unpacks the underlying mechanisms involved in diverse motor tasks and describes more specifically how various measures map onto achievement and school performance outcomes at different points in the transition to school. Illuminating and testing specific questions about the processes, including motor skills, that underlie school success but that are not in the policy spotlight will enhance our capacity to help children acquire the skills they need to do well in school and life.

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