Received: 13 June 2020 | Revised: 18 November 2020 | Accepted: 20 November 2020

DOI: 10.1111/desc.13071

Developmental Science WILEY

SHORT REPORT

Short report: Improving motor competence skills in early childhood has corollary benefits for executive function and numeracy skills

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Funding information
Institute of Education Sciences, Grant/Award Number: R305A160035

Abstract

Previous studies have documented that individual differences in fine and gross motor skills are associated with executive function (EF) skills. This study used an experimental design to test whether participating in cognitively challenging motor skills activities was causally related to improvements in motor skills and two key indicators of school readiness: executive function and early numeracy skills. The motor skill program involved fine and gross motor game-like activities that were delivered in a small group format. Activities were socially engaging and progressively challenged children based on their motor competencies. Fifty-three preschool-aged children participated in 16 motor skill sessions across 8 weeks. There were significant treatment effects for all outcomes, such that children in the treatment condition exhibited significant improvements in motor, EF, and early numeracy skills, compared to their peers in the waitlist control condition. Treatment effects on EF skills were stronger for inhibitory control than working memory. Improvements in numeracy were most pronounced for children with initially lower levels of ability. Motor skill-based interventions are an ecologically valid and developmentally appropriate approach for fostering school readiness skills in early childhood.

KEYWORDS
early childhood, executive function, fine motor, gross motor, intervention, numeracy

1 | INTRODUCTION

Early childhood represents a period of rapid development that is characterized by improvements in children's capacity to engage in goal-directed behavior and problem solving by carefully planning, monitoring, and controlling thoughts and actions (Garon et al., 2008; Munakata et al., 2012). These higher-order cognitive processes are collectively referred to as executive function (EF) skills (Zelazo et al., 2016). EF skills are considered to be domain general because they contribute to multiple aspects of development, including behavioral competence, pre-academic skill acquisition, and peer and adult social relationships—all of which contribute to a successful transition to formal schooling and long-term academic success (Blair & Raver, 2015). As such, there is widespread interest in improving EF skills in early childhood to promote school readiness.

A variety of approaches have been used to improve EF skills in children, including computerized cognitive training programs (e.g., CogMed) (Aksayli et al., 2019), classroom curricula (e.g., Tools of the Mind) (Barnett et al., 2008), and mindfulness practices (see Takacs & Kassai, 2019). However, the magnitude of effects has been variable, and, in the case of cognitive training programs, questions remain about whether narrowly trained skills result in improvements in untrained areas (e.g., whether improved working memory skills foster improved academic achievement) (Diamond & Ling, 2020). Current recommendations for improving EF skills in children emphasize activities that are (a) authentically embedded into everyday activities (b) continually challenging, and (c) richly focused on social engagement (Diamond & Ling, 2016, 2020).

Theoretically, physical activity-based approaches have the potential to align with recommendations for best practice, but the utility of these approaches in early childhood is a source of debate (Diamond & Ling, 2018; Hillman et al., 2018). In a review of 45 studies, Diamond and Ling (2020) concluded that physical activity interventions that focus narrowly on quantitative characteristics of exercise (e.g., intensity, duration, and frequency) provide little to no improvement in EF skills in children. In contrast, programs that emphasize qualitative characteristics of exercise provide more promising results. For example, team sports create opportunities for cognitively challenging skills development in socially meaningful contexts. Importantly, the existing literature has primarily focused on middle childhood and adolescence, with comparatively less work in early childhood, which is a time when EF skills are rapidly developing.

Children's gross and fine motor skills are also rapidly developing during early childhood (Clark & Metcalfe, 2002). The motor demands of various activities are an important qualitative feature of physical activity during this developmental period. Whereas gross motor skills involve coordinating the body's large muscles to obtain balance and to move the trunk and limbs efficiently (e.g., running, throwing or catching a ball), fine motor skills involve visuomotor integration to precisely coordinate small muscle movements (e.g., building with blocks, puzzles, tracing or copying) (Davis & Matthews, 2010; Gallahue et al., 2012; Korkman et al., 2007). Although children's gross and fine motor skills become increasingly coordinated as a result of normative development (Adolph, 2005, 2008; Clark, 2005), motor competence develops more rapidly when skills are explicitly taught and intentionally practiced through planned movement activities that are developmentally appropriate (Brian et al., 2016; Clark, 2005; Goodway & Branta, 2003). To the extent that learning and practicing new motor skills involves planning, monitoring, and controlling coordinative actions (Adolph, 2005), motor skills interventions represent an unexplored approach to facilitating EF skill development, which is known to support pre-academic skill acquisition, in early childhood.

Numerous observational studies that involve preschool-aged children have documented positive associations between children's EF skills and their gross (Cook et al., 2019; Stein et al., 2017; Wassenberg et al., 2005) and fine motor skills (Becker et al., 2014; MacDonald et al., 2016; Oberer et al., 2018). EF and motor skills also make unique contributions to academic achievement during preschool and at kindergarten entry (Cameron et al., 2012, 2015), which had led researchers to suggest that motor and EF skills co-develop, with gains in one area leading to corresponding gains in the other (Cameron et al., 2016; Leonard & Hill, 2015; McClelland & Cameron, 2019). Although promising, the correlational nature of these studies limits clear inferences about the extent to which (and in what direction) cognitive and motor skills are causally related.

Research Highlights

- Children were randomized to participate in a small-group motor skills program that consisted of cognitively challenging gross and fine motor activities that were designed to foster EF.
- Children who participated in treatment groups demonstrated gains in motor competence, executive function (especially inhibitory control), and numeracy skills.
- Improvements in numeracy were most pronounced for children with initially lower levels of performance.
- Motor skill-based interventions that are socially engaging and progressively challenging represent a developmentally appropriate approach for improving executive function skills in early childhood.

At least 21 studies have been published that describe motor skills interventions involving typically developing preschool-aged children (for a review see Logan et al., 2011; Riethmuller et al., 2009; Strooband et al., 2020). However, we are only aware of three studies that used experimental designs to test whether motor skills interventions that were delivered in early childhood had corollary benefits on school readiness skills, including EF skills and pre-academic achievement (Brock et al., 2018; Mulvey et al., 2018; Pienaar et al., 2011). In an evaluation of a perceptual-motor development program (i.e., *Kinderkinetics*), Pienaar et al. (2011) reported improvements in children's motor skills but not their verbal or numerical skills. In contrast, in an evaluation of a structured gross motor program (i.e., *Successful Kinesthetic Instruction for Preschoolers*), Mulvey and colleagues reported improvements in gross motor and behavioral regulation skills relative to their peers who participated in unstructured recess activities (Mulvey et al., 2018). Behavioral regulation was measured by the Head Toes Knees Shoulders (HTKS) task (Ponitz et al., 2009). Given the inherent motor demands required to complete the HTKS, it is unclear if children's improvement on this task reflected improved cognitive and/or motor skills. Finally, in an evaluation of a visuomotor program (i.e., *Minds in Motion*) that was delivered to kindergarten-aged children in an after-school program, Brock and colleagues reported improvements in children's attention, inhibitory control, and cognitive flexibility (Brock et al., 2018). Two of the three of these studies suggest that efforts to enhance young children's motor skills have corollary benefits on cognition.

In sum, children's gross and fine motor skills are malleable and responsive to intervention during early childhood. It remains unclear whether these gains are causally related to improvements in other domains of school readiness, including EF development and the acquisition of pre-academic skills. The current study is a small-scale test of whether a cognitively challenging fine and gross motor skill development program improves preschool-aged children's motor competence, EF, and numeracy skills. Notably, the motor skills program is aligned with current recommendations for improving EF skills, including embedding structured and progressively complex motor skill challenges into small group, game-based activities.

2 | METHODS

2.1 | Participants and procedures

A total of 53 children (3–5 years old) were recruited from two preschools in the Southeastern United States to participate in the Kids Activity and Learning Study (KALS). Children were an average of 4.3 years old (*SD* = 0.6, range = 3.2–5.2 years). Females outnumbered males (58% female), and 60% of children were enrolled in a Head Start Center (the remainder were in a private preschool). Children completed pretest assessments in August-September and were subsequently randomly assigned to experimental (N = 27) or wait-list control (N = 26) conditions. Randomization of all consented children occurred within classrooms to control for any classroom-level differences that may have contributed to student outcomes. Students in the experimental group were assigned to participate in the motor skills intervention in the fall (September-December), while those in the control group were assigned to participate in the spring (January-April). All children in the treatment and waitlist control conditions completed posttest assessments immediately after the conclusion of the fall intervention period (December). To maintain objectivity, the research team member who was involved in delivering the motor skills intervention did not complete any motor assessments at the posttest assessment. The RTI International Institutional Review Board approved all study activities.

2.2 | Motor skills curriculum

A comprehensive motor skills curriculum was developed to target children's gross and fine motor skills. Gross motor activities were selected from *Young Athletes*, an evidenced-based gross motor program that provides detailed lesson plans to facilitate 2- to 7-year-old children's object control and locomotor skills as well as stability, balance, and bilateral coordination (Favazza et al., 2013). We supplemented gross motor lesson plans from *Young Athletes* with fine motor activities from the *FingerGym* curriculum (Brook et al., 2006). The *FingerGym* curriculum is a commercially available preschool and kindergarten school readiness program that targets fine motor skills, including visuomotor integration and manual dexterity. Activities from each program that were developmentally appropriate for 3- to 5-year old children and could be implemented in small groups in a preschool center setting were selected. Informed by Diamond and Ling's (2016) recommendations, all activities were modified to be adaptive so that children with varying motor abilities were continually and appropriately challenged within and across sessions. All motor skill development sessions were conducted in small-group, pull-out format (four children per group). The small-group format facilitated staff efforts to encourage supportive and positive peer interactions (e.g., children with more advanced motor skills often encouraged their peers who needed assistance to complete activities). The pull-out format allowed group composition to vary across weeks (i.e., the selection of children for each session was contingent on their attendance and availability given ongoing classroom activities).

A total of 50 unique game-based activities (28 gross motor and 22 fine motor) were adapted from *Young Athletes* and *FingerGym* and integrated into 16, 30-minute lesson plans that targeted specific gross motor (e.g., locomotor, object control, stability) and fine motor (e.g., manual dexterity, visuomotor integration) skills. A sample lesson plan is provided in Supplementary Materials (and the full set of lessons are available upon request). Children attended motor skill development sessions twice a week for 8 weeks, which resulted in up to 8 h of skill development (320 min allocated to gross motor and 160 min allocated to fine motor development)[1]. On average, children completed 14.6 of 16 sessions (*Range* = 10–16), which was consistent at both preschools (*Ms* = 14.5 and 14.77).

Each session was led by the same research staff member who delivered motor activities in a game-like format, which increased student engagement. The staff member monitored student performance and individualized activities whenever possible using the specified skill progressions and regressions provided in each activity lesson. To illustrate, during activities that targeted jumping skills, children who needed additional challenge were encouraged to try jumping on one foot or to jump farther distances. In contrast, children who needed additional assistance were encouraged to practice jumping by leaning forward and bending their knees. The study coordinator observed 20% of lessons at each preschool to ensure the motor skills curriculum was implemented with fidelity. The fidelity checklist assessed adherence to the lesson script and time limit, appropriate demonstration of the activities, and provision of appropriate modifications dependent on children's skill level. Following each fidelity visit, the study coordinator and activity leader reviewed the fidelity checklist and discussed any deviations from the lesson plan that occurred.

2.3 | Measures

2.3.1 | Executive function touch

EF Touch is a computerized battery of tasks that provide performance-based indicators of preschool-aged children's inhibitory control, working memory, and attention shifting skills (Willoughby & Blair, 2016). Children completed an average of six of the seven tasks they were presented (i.e., three inhibitory control, two working memory, one attention shifting, and one simple reaction time) at pre and posttest assessments. The EF Touch battery has undergone extensive psychometric evaluation (Willoughby, Wirth, et al., 2012). Collectively, these studies have demonstrated that individual tasks measure the full range of children's ability. Following precedent (Willoughby et al., 2016), we constructed overall EF, inhibitory control, and working memory composite scores by taking the mean performance across all relevant tasks (i.e., six tasks for EF, three tasks for inhibitory control, two tasks for working memory).

2.3.2 | Woodcock-Johnson IV: Applied problems subtest.

The WJ-AP, which is part of the WJ-IV battery of psychoeducational tests, is a standardized assessment of quantitative abilities consisting of a series of oral math word problems (Schrank et al., 2014). The WJ-IV has been norm referenced using a national sample of individuals between 2 and 90 years old. The reliability and validity of the WJ-IV is well-established (Villarreal, 2015). Previous iterations of the WJ have been used extensively in the early childhood literature, and the WJ-AP is positively correlated with performance on the EF touch battery (Willoughby, Blair, et al., 2012).

2.3.3 | Bruininks-Oseretsky Test of Motor Proficiency Short Form—Second Edition

The Bruininks-Oseretsky Test of Motor Proficiency Short Form—Second Edition (BOT-2) is a norm-referenced measure of motor competence (Bruininks & Bruininks, 2005). Given time constraints, we used the short form of the BOT-2, which consists of 14 items from the BOT Complete Form. It took approximately 15 min to complete. Example tasks include drawing a path between lines, standing with one leg on a portable balance beam, and walking along a straight line. The reliability and validity of the BOT-2 short and complete forms are well-established (Bruininks & Bruininks, 2005). Raw scores were used because norm-referenced scores were not appropriate for children who were younger than 4 years of age in our sample.

2.4 | Analytic strategy

Analyses proceeded in three phases. First, we used independent samples t-tests to investigate whether randomization was effective (i.e., whether children in the treatment and wait-list control groups did not differ from each other on motor competence, EF, or math skills performance at pretest). Second, we fit a series of analysis of covariance (ANCOVA) models to test whether children who participated in the treatment condition exhibited improvements in motor competence, EF, and/or math outcomes. Child age, the child's pretest score, and preschool membership (dummy coded to distinguish two preschools) were included as covariates to control for any preexisting differences between children and schools, as well as to improve statistical power. Third, we re-estimated each ANCOVA model to include a treatment x pretest interaction, which provided an exploratory test of whether the magnitude of any treatment effect varied as a function of children's pretest skills. Given the small sample size, we computed and emphasized Cohen's d effect sizes throughout. Effect sizes were computed by taking the difference between least squares means from ANCOVA models and dividing that difference by the total sample pooled standard deviation of each outcome at pretest. We could not model the hierarchical data structure because of the small sample size and the inconsistent composition of activity groups.

3 | RESULTS

3.1 | Sample description and descriptive statistics

Intervention and wait-list control groups did not differ regarding child age or gender. Unadjusted group differences for all outcome variables are summarized in Table 1. The intervention and control groups did not differ at pretest regarding the number of EF tasks they completed, their performance on EF composites, or their performance on the math achievement task. Although not statistically significant, children assigned to the intervention group had higher pre-existing motor competence skills (M = 28.41, SD = 12.83) than children in the control condition (M = 20.96, SD = 8.72) (p = .06 *Cohen d* = .52).Bivariate correlations among study outcomes are summarized in Table 2. Consistent with previous studies, motor competence, EF, and numeracy skills were all strongly positively correlated at pretest and posttest assessments (*rs* ≈ .4–.6, *ps* < .01). Descriptively, motor competence appeared more strongly associated with inhibitory control (*rs* = .61 and .53 at pre- and posttest, respectively, *ps* < .0001) than working memory (*rs* = .23 and .30 at pre- and posttest, respectively, *ps* = .11 and .04). Scores for individual assessments were highly stable across pretest and posttest assessments (*rs* = .39–.92, all *ps* < .01; see diagonal of Table 2). Strong associations between pretest and posttest scores increase power to detect treatment effects because of a reduction in error variance.

3.2 | Treatment effects

The results from ANCOVA models are summarized in Table 3. Except for working memory, there were significant main effects for treatment for all outcomes. Compared to their peers in the wait-list control condition, children who participated in the motor skills intervention demonstrated small to moderate increases in motor competence (p = 0.03, *Cohen d* = .29), overall EF (p = 0.04, *Cohen d* = .41), and numeracy (p = 0.03, *Cohen d* = .24) skills. Descriptively, the treatment effects appeared stronger for inhibitory control than working memory (*Cohen ds* = .54 vs. .15, respectively). Although not presented, for each outcome of interest (e.g., motor, EF, and numeracy) performance at pretest was the only consistently significant covariate across models.

TABLE 1 Descriptive statistics and unadjusted group comparisons

		Total Sample		Treatment	Control	Compare
Outcome	Assessment	*N*	*M (SD)*	*M*	*M*	*t (df)*
BOT–2	Pre	53	20.1 (12.3)	23.2	16.8	−1.9 (51)+
	Post	52	24.8 (11.6)	28.4	21.0	−2.4 (50)*
EF Tasks	Pre	53	6.1 (1.4)	6.3	5.9	−1.1 (51)
	Post	53	6.3 (1.2)	6.6	5.9	−2.1 (51)*
EFcomp	Pre	52	58.2 (13.2)	59.3	57.0	−0.6 (50)
	Post	53	62.9 (16.0)	67.2	58.3	−2.1 (51)*
ICcomp	Pre	51	55.6 (20.9)	57.1	54.1	−0.5 (49)
	Post	51	62.3 (24.1)	69.1	54.6	−2.2 (49)*
WMcomp	Pre	52	58.5 (12.0)	57.4	59.7	0.7 (50)
	Post	51	62.0 (13.2)	62.7	61.2	−0.4 (49)
WJ-AP	Pre	52	91.8 (17.9)	94.1	89.2	−1.0 (50)
	Post	52	93.0 (16.7)	96.6	89.1	−1.6 (50)

BOT-2, motor proficiency; *df*, degrees of freedom; EFcomp, executive function composite; ICcomp, Inhibitory control composite; *M*, mean; *N*, sample size; *SD*, standard deviation; *t*, t distribution test statistics; WJ-AP, Woodcock-Johnson Applied Problems; WM, Working memory composite.

+*p* < .10,

**p* < .05,

***p* < .01,

****p* < .001

TABLE 2 Bivariate correlations among study outcomes at pretest (below diagonal) and posttest (above diagonal)

	1.	2.	3.	4.	5.
1. BOT–2	0.88***	0.53***	0.50***	0.30*	0.42**
2. EFcomp	0.61***	0.72***	0.93***	0.69***	0.47***
3. ICcomp	0.61***	0.93***	0.64***	0.39**	0.38**
4. WMcomp	0.23	0.57***	0.31*	0.39**	0.39**
5. WJ-AP	0.51***	0.49***	0.40**	0.36**	0.92***

Note: Values along the diagonal indicate the stability of values from pre to posttest.

Abbreviation: BOT-2, motor proficiency; EFcomp, executive function composite; ICcomp, Inhibitory control composite; WJ-AP, Woodcock-Johnson Applied Problems; WM, Working memory composite.

**p* < .05,

***p* < .01,

****p* < .001

3.3 | Conditional treatment effects

The previous ANCOVA models provide an estimate of overall treatment effects. Next, we conducted an exploratory analysis to determine if children differentially benefitted from treatment. Specifically, we re-estimated ANCOVA models to include a treatment x pretest term. The treatment x pretest term was only statistically significant for numeracy skills, $F\,(1, 45) = 5.00$, $p = 0.03$. We probed this interaction by examining treatment effects at low, medium, and high levels of pretest performance (defined as 25th, 50th, and 75th percentile scores for this sample). As depicted in Figure 1, children who had initially lower performance on numeracy skills benefitted more (*Cohen d* = 0.38, *p* = .003) than children who had initially moderate (*Cohen d* = .17, *p* = .11) or high (*Cohen d* = .09, *p* = .44) levels of skills.

4 | DISCUSSION

Significant treatment effects were observed for all outcomes. In comparison to their peers in the waitlist control condition, children who participated in a comprehensive motor skills program demonstrated significant improvements not only in their motor skills but also their EF and early numeracy skills. Regarding EF skills, the motor skills program had a greater impact on inhibitory control than working memory. Improvements in numeracy were most pronounced for children with initially lower levels of performance. These results are discussed in turn.

This study extends previous experimental findings reported in three ways. First, our findings are consistent with those reported by Brock et al. (2018) and build on the those reported by Mulvey et al. (2018) by demonstrating gains in EF skills on nonmotor-based tasks. Mulvey et al. (2018) use of the HTKS task (Ponitz et al., 2009), which has inherent motor demands, left uncertain whether improvements in HTKS reflect EF or motor skills. Second, our study is the first to indicate that preschool-aged children's participation in a cognitively challenging motor skills program can result in improved numeracy skills. The impact of motor skills on numeracy may reflect a direct effect (i.e., improved fine motor coordination skills may support the use of math manipulatives, which are frequently used for math instruction in preschool classrooms) or an indirect effect (i.e., improved motor coordination skills improved EF skills that are known to be associated with school readiness skills, including pre-academic skill acquisition

TABLE 3 Summary of treatment effects

Outcome	Model: F (ndf, ddf)	Model: Adjusted R^2	Compare: F (ndf, ddf)	Compare: Cohen d	Treatment: LSM	Control: LSM
BOT–2	51.6 (4, 47)***	0.81	4.90 (1,47)*	0.29	26.6	23.3
EFcomp	15.5 (4, 47)***	0.57	4.57 (1, 47)*	0.41	66.2	59.7
ICcomp	10.9 (4, 45)***	0.49	6.36 (1, 45)*	0.54	68.5	55.5
WMcomp	2.8 (4, 46)*	0.19	0.33 (1, 46)	0.15	63.2	61.2
WJ-AP	77.2 (4, 46)***	0.87	4.84 (1, 46)*	0.24	95.3	91.4

Note: The model and compare columns summarize tests of overall model fit and treatment group differences respectively. All models included child age, preschool, and the pretest value for each outcome as covariates.

BOT-2, motor proficiency; *ddf*, denominator degrees of freedom; EFcomp, executive function composite; *F*, F distribution test statistic; ICcomp, Inhibitory control composite; *LSM*, least squares mean; *ndf*, numerator degrees of freedom; WJ-AP, Woodcock-Johnson Applied Problems; WM, Working memory composite.

*$p < .05$,

**$p < .01$,

***$p < .001$.

such as numeracy) (McClelland & Cameron, 2019). Our study is unable to distinguish these possibilities. Third, our findings suggest that a comparatively lower treatment dosage is effective when paired with a balanced provision of progressively challenging gross and fine motor activities. In the current study, we provided a total of 8 hours of skill development with approximately 5 h devoted to gross and 3 h devoted to fine motor activities. As a point of comparison, Mulvey et al. (2018) provided a total of 6 h of gross motor activities whereas Pienaar et al. (2011) provided approximately 19 h of gross and 2 h of fine motor activities. Brock et al. (2018) provided 72 h of fine motor activities and reported that study staff were prepared to implemented gross motor activities on an as-needed basis when children needed a break or completed fine motor tasks early.

Although promising, our findings are preliminary and should be interpreted with caution. At least three limitations are noteworthy. First, although an experimental design was used, an active control condition (as opposed to a business as usual waitlist control), would provide a stronger test of intervention effects. It is also worth noting that despite random assignment to condition, differences in motor skills between groups were present at pre-test such that children in the treatment condition performed better on the BOT-2 (Bruininks & Bruininks, 2005) at the initial assessment compared to their peers in the waitlist control condition. Although pre-existing differences in motor competence between groups did not reach conventional levels of significance, we nonetheless control for children's initial motor performance in our analyses examining motor performance at pretest. Our interpretation of results reflects the effect of the intervention over and above children's initial performance. Second, the small-scale implementation of the KALS motor skills program was influenced by a broad set of project-related constraints. To facilitate child engagement, motor skill sessions took places in small groups (four children per group) with one research staff member in two preschools. However, the small-group format also posed a logistical challenge and constrained our sample size could only conduct three or four group sessions per day, depending on preschool schedule, prior to lunch and afternoon naptime. Third, group composition varied across individual activity sessions, such that the same four children did not always attend the same

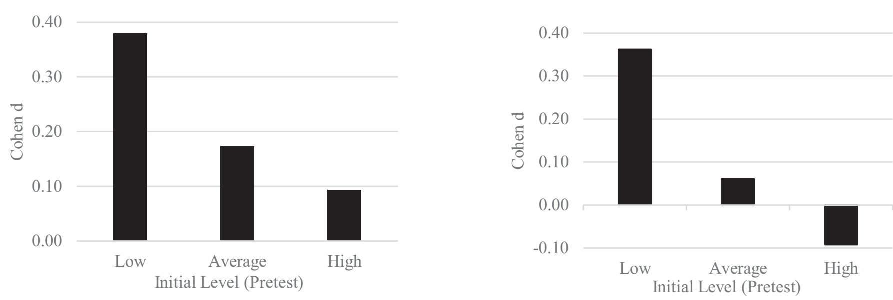

FIGURE 1 Conditional treatment effects were examined at low, medium, and high levels of pretest performance (defined as 25th, 50th, and 75th percentile scores for this sample). As shown in the left panel, children who had initially lower levels of performance on numeracy skills at pretest benefitted more than children who had initially higher levels of performance. Although not statistically significant, the right panel displays a similar pattern of results for working memory skills

session. Although children were randomly assigned to the intervention or wait-list control group at the classroom level, inconsistencies in children's arrival time and daily attendance, as well as changes to classroom schedules to accommodate special activities, resulted in variations in small-group composition over the course of the 8-week intervention. As a result, we were unable to account for the hierarchical structure of the data.

Despite these limitations, our findings demonstrate the initial promise of using a motor skills intervention to improve children's cognitive outcomes. Additional research is needed to further examine differential treatment effects. We documented greater improvements in numeracy for those children with initially lower levels of performance but did not observe a pattern of similar differential benefit motor or EF skills. Although it seems reasonable to expect that children with initially lower levels of performance stand to benefit the most from intervention we made a deliberate effort to provide individualized skill progressions and regressions as needed so that all children were engaged in cognitively challenging motor activities that require carefully planning, monitoring, and controlling actions. From this perspective we would expect that all children would benefit equally. It also remains to be seen whether improvement in fine versus gross motor skill differentially contribute to EF and numeracy development. In the current study, we used the BOT-2 Short Form (Bruininks & Bruininks, 2005) to assess motor competence, which does not permit separate consideration of fine and gross motor skills. Expanded assessment is needed to provide a thorough test of intervention effects on fine and gross motor skills individually. Finally, the current study only examines the acute effects of intervention. Future research should examine the extent to which treatment effects will persist or whether continued intervention efforts are needed to maintain effects over time.

Developmental scientists have long appreciated and drawn attention to the ways in which motor development contributes to cognition (Diamond, 2000; Thelen, 1995). Yet much of the existing literature on the motor-cognitive link has been carried out with infants and toddlers (Campos et al., 2012; Gottwald et al., 2016; Veldman et al., 2019) and children with developmental disabilities (Diamond, 2000; Weierink et al., 2013). The current study adds to a growing body of evidence that motor skill development is causally related to cognitive development for typically developing preschool children. Identifying effective approaches to facilitating to the development of preschool-aged children's EF skills is especially important given that EF skills undergo rapid development during early childhood and promote school readiness and academic achievement. Compared to traditional cognitive training programs that aim to improve EF skills, cognitively challenging motor skill-based interventions have the potential to be more developmentally appropriate and socially engaging. The fact that motor skill-based interventions improve children's functioning in multiple domains is consistent with the interdependent nature of early development and holds promise for leveraging key tenets of developmental science to enhance children's well-being.

ACKNOWLEDGMENTS

This study was supported by the Institute of Education Sciences grant R305A160035. The views expressed in this manuscript are those of the authors and they do not necessarily represent the opinions and positions of the funders.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENDNOTE

[1] We examined 21 motor skills interventions conducted with typically developing preschool-aged children (for a review see Logan, Robinson, Wilson, & Lucas, 2011; Riethmuller, Jones, & Okely, 2009; Strooband, Rosnay, Okely, & Veldman, 2020). Eighteen studies reported dosage that ranging 5 to 60 hours. The total dosage in the current study is consistent with median dosage reported (11.65 hours).

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How to cite this article: Hudson KN, Ballou HM, Willoughby MT. Short report: Improving motor competence skills in early childhood has corollary benefits for executive function and numeracy skills. *Dev Sci*. 2020;00:e13071. https://doi.org/10.1111/desc.13071