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Relations between fine motor skills and intelligence in typically developing children and children with attention deficit hyperactivity disorder

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ABSTRACT

Background: The embodied cognition hypothesis implies a close connection between motor and cognitive development. Evidence for these associations is accumulating, with some studies indicating stronger relations in clinical than typically developing samples.
Aims: The present study extends previous research and investigates relations between fine motor skills and intelligence in typically developing children (n = 139, 7–13 years) and same-aged children with attention deficit hyperactivity disorder (ADHD, n = 46). In line with previous findings, we hypothesized stronger relations in children with ADHD than in typically developing children.
Methods and procedure: Fine motor skills were assessed using the standardized Movement Assessment Battery for Children. Intelligence was measured with the standardized Wechsler Intelligence Scale for Children.
Outcomes and results: Regression analyses indicated significant relations between fine motor skills and full-scale IQ, perceptual reasoning, working memory, and processing speed. Moderation analyses identified stronger relations between fine motor skills and full-scale IQ, perceptual reasoning, and verbal comprehension in children with ADHD compared to typically developing children.
Conclusions and implications: Results suggest a close relation between fine motor skills and intelligence in children with and without ADHD, with children diagnosed with ADHD showing stronger relations. Findings support combined motor-cognitive interventions in treating children with ADHD.

What this paper adds

The current study investigated relations between fine motor skills and intelligence in typically developing children and children with attention deficit hyperactivity disorder (ADHD). Previous research has examined small and heterogenous clinical samples, including children with multiple developmental disabilities. By contrast, the present study used a large homogeneous sample of children with ADHD which allows specific implications. Furthermore, recent studies have mainly investigated samples of typically developing children at the age of kindergarten and their transition to school. The present sample extends these studies by examining

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the association between fine motor skills and intelligence across childhood to early adolescence. Analyses of intelligence considered the full-scale IQ as well as the four subcomponents (perceptual reasoning, verbal comprehension, working memory, and processing speed) for detailed insight and specific conclusions. Results have high theoretical and practical value for creating effective motor-cognitive interventions in treating children with ADHD.

1. Introduction

Motor and cognitive abilities are often assumed to be deeply connected. Whereas some researchers have proposed that motor skills are linked with developmental changes in cognition (e.g., Adolph & Joh, 2007), others named motor skills as foundation for cognitive development (e.g., von Hofsten, 2009). Explanations historically refer to Piaget's theory, who proposed that the sensorimotor stage is the initial stage of adaptation in cognitive development: infants create learning opportunities through self-initiated actions (Piaget, 1947). More recently, the embodied cognition perspective attempted to explain the link between motor and cognitive abilities beyond simple age-related changes (Barsalou, 1999; Gibbs, 2005). According to this theory, executing a new motor skill facilitates cognitive processes in infants and children as they discover new aspects in their environment which helps shaping their perception, and enables new opportunities to interact with objects and people (Gottwald, Achermann, Marciszko, Lindskog, & Gredeback, 2016; Harbourne & Berger, 2019).

In line with this embodied cognition account, correlational studies showed associations between infants' motor development and concurrent spatial abilities (e.g., Schwarzer, Freitag, Buckel, & Lofruthe, 2013), later language (e.g., Oudgenoeg-Paz, Volman, & Leseman, 2012) and categorization skills (e.g., Murray et al., 2006). In addition, experimental studies point to the causal relation between infants' motor experience and object exploration skills (e.g., Libertus, Joh, & Needham, 2016), spatial abilities (e.g., Möhring & Frick, 2013), and executive functioning (e.g., Berger, 2010). Importantly, these effects are not restricted to infancy but seem to continue into childhood and adulthood (for reviews, see Berger, Harbourne, & Horger, 2018; Frick, Möhring, & Newcombe, 2014; Kontra, Goldin-Meadow, & Beilock, 2012).

Further evidence for a close link between motor and cognitive skills comes from their similar developmental trajectories and an overlap of activated neural areas (e.g., cerebellum, dorsolateral prefrontal cortex; Diamond, 2000). The majority of research investigating this topic has focused on typically developing children (Frick & Möhring, 2016; Piek, Dawson, Smith, & Gasson, 2008, 2004; Rigoli, Piek, Kane, & Oosterlaan, 2012; Roebers & Kauer, 2009; Wassenberg et al., 2005), with evidence from clinical populations being less well studied. Some of this research with clinical samples has indicated that children with developmental disorders that are predominantly associated with attention deficits often show co-morbidities with motor problems (cf. Diamond, 2000). For example, many children with attention deficit hyperactivity disorder (ADHD) do not only show attention deficits but also impaired motor skills (for a review, see Kaiser, Schoemaker, Albaret, & Geuze, 2015). In particular, 30–50 % of children with ADHD meet the diagnostic criteria of a comorbid Developmental Coordination Disorder (Fliers et al., 2008, Kadesjo & Gillberg, 1998; Sergeant, Piek, & Oosterlaan, 2006).

Based on these latter studies, it seems likely that motor and cognitive skills are related in typical and clinical populations. To date, only few studies have investigated these relations in typical and clinical samples in a single unified approach (e.g., Smits-Engelsman & Hill, 2012). Crucially, these studies demonstrate that associations between motor and cognitive skills seemed to be stronger in clinical groups as compared to typically developing children. For example, Dyck, Piek, Hay, Smith, and Hallmayer (2006) investigated relations between motor coordination and language skills in children aged 6–15 years with autism spectrum disorder (ASD) and controls and found stronger relations in the clinical sample. Likewise, another study examined 1- to 10-year-old children with intellectual and developmental disabilities (e.g., children with Down syndrome) and showed stronger correlations among motor, cognitive, and language measures as compared to typically developing children matched for developmental age (Houwen, Visser, van der Putten, & Vlaskamp, 2016). With respect to explanations for these differential patterns, several authors suggested an unusual interdependence among neurocognitive processes in children with developmental disabilities (Dyck et al., 2006; Houwen et al., 2016). This explanation is supported by findings showing that movement problems in children with ADHD have been associated with a disbalance of basal ganglia neurocircuitries (Archer & Beninger, 2007).

Further evidence for different relations between motor performance and intelligence in clinical populations as compared to controls was investigated in children with acquired and congenital disorders (e.g., traumatic brain injury, ADHD) and healthy, typically developing children (Martin, Tigera, Denckla, & Mahone, 2010). Participants were examined with a standardized intelligence measure and a simple repetitive and a more complex sequenced motor task. Results demonstrated that in both samples, higher intelligence was related to better performance in the complex motor task. However, intelligence and performance in the simple motor task was only correlated in the clinical sample but not in typically developing children. The authors suggested that atypical neurodevelopmental processes in the clinical sample caused this pattern of results. In accordance with the model of motor learning (cf. Fitts and Posner, 1967), motor skills become increasingly automatized across development and thus, require less cognitive resources. In light of this model, findings of Martin et al. (2010) could also be explained by assuming that motor control required a high level of cognitive resources for the complex motor task in both samples, but may have been more automatized in case of the simple motor task in typically developing children. As a consequence, typically developing children may have shown lower interindividual variability in the simple motor task of this respective study, providing less shared variance with the intelligence measure.

The studies investigating different relations between cognitive and motor skills in typical and clinical samples (Houwen et al., 2016; Martin et al., 2010) have mainly used very heterogenous samples including children with various diagnoses (with the exception of Dyck et al., 2006 who examined children with ASD). Even though such an approach is informative, it precludes the possibility to make specific conclusions for children with particular developmental disabilities. The current study aimed at extending previous research and investigated relations between cognitive and motor skills using a large, homogenous sample of children diagnosed with ADHD. It is of particular interest to investigate this specific clinical sample because ADHD is one of the most prevalent diagnosed developmental disorders in childhood affecting many children (Willcutt, 2012), and children with ADHD have difficulties in attention and often co-occurring motor problems (Kaiser et al., 2015).

Considering that previous research suggests that fine motor skills showed stronger relations to cognition as compared to gross motor skills (van der Fels et al., 2015), the present study focused specifically on this set of skills. Fine motor skills are defined as the ability to control small muscle movements to accomplish a task using hand-eye coordination, fine motor precision, and integration (Luo, Jose, Huntsinger, & Pigott, 2007; Magill, 1996). Evidence for associations between fine motor and cognitive skills comes mainly from research with typically developing kindergarteners. For example, cross-sectional and longitudinal studies showed that fine motor skills significantly contributed to children's kindergarten achievement (Cameron et al., 2012), as well as reading and mathematical achievement (Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010). Additionally, research demonstrated relations between fine motor skills and intelligence in typically developing children aged 4–11 years (Davis, Pitchford, Jaspan, McArthur, & Walker, 2010; Davis, Pitchford, & Limback, 2011; Roebers et al., 2014). However, considering that fine motor skills develop well into adolescence (Diamond, 2000), it is rather surprising that only few studies focused on older children. The current study begins to fill this gap by focusing on children up to adolescence.

The current study investigated relations between fine motor skills and intelligence in typically developing children and children with ADHD. Fine motor skills and intelligence were assessed with standardized instruments to enable comparability with previous research (e.g., Roebers et al., 2014). Additionally, investigating aged-normalized values enables to examine the relations between fine motor skills and intelligence beyond simple age effects. Analyses were conducted for full-scale IQ as well as for the four subcomponents of intelligence (verbal comprehension, perceptual reasoning, working memory, and processing speed), thus looking at specific associations between aspects of intelligence and fine motor skills. Additionally, to determine whether children with ADHD show stronger relations between fine motor skills and intelligence as compared to typically developing children, a series of moderated regression analyses was conducted.

2. Methods

2.1. Participants

Two-hundred and twenty children aged 7–13 years participated in the present study. Participants with missing data in the key variables were excluded ($n = 35$). Therefore, the final sample consisted of $n = 185$ children, of which 139 were typically developing children and 46 were children diagnosed with ADHD (for sample characteristics, see Table 1). The majority of participants came from Switzerland (94 %), other European countries, American and African countries. Typically developing children were recruited from local schools. Children were included in the study when showing sufficient German language skills and when the parental questionnaire confirmed that they did not have any developmental or psychopathological diagnosis. Children with ADHD were recruited from the University Children's Hospital in Basel or local pediatricians after being diagnosed with ADHD according to criteria of the DSM-IV or ICD-10. The majority of children with ADHD ($n = 33$) was treated with stimulant medication such as methylphenidate and

Table 1
Descriptive statistics and group differences in the key variables between typically developing children and children diagnosed with attention deficit hyperactivity disorder.

	Typically developing children (n = 139)		*Children with ADHD (n = 46)*		
Variable	*N (%) / M (SD)*	*Range*	*N (%) / M (SD)*	*Range*	*P*
Sex					.002**
Male	76 (54.7 %)		37 (80.4 %)		
Female	63 (45.3 %)		9 (19.6 %)		
Maternal education	4.81 (1.33)	2 – 6	3.80 (1.31)	2 – 6	.000***
No school degree	0 (0%)		0 (0%)		
Mandatory school	2 (1.4 %)		4 (8.7 %)		
Apprenticeship	39 (28.1 %)		24 (52.2 %)		
High school	10 (7.2 %)		3 (6.5 %)		
Higher education	21(15.1 %)		7 (15.2 %)		
University / college	67 (48.2 %)		8 (17.4 %)		
Age (in years)	10.06 (1.45)	7 – 13	10.64 (1.59)	7 – 13	.023**
Fine motor skills	10.00 (2.66)	2 – 17	7.72 (2.44)	3 – 14	.000***
Full-scale IQ	106.22 (10.52)	84 – 136	93.33 (13.98)	70 – 129	.000***
Perceptual reasoning	34.94 (5.50)	21 – 49	29.74 (6.89)	17 – 42	.000***
Verbal comprehension	32.32 (6.06)	20 – 51	28.57 (6.63)	18 – 44	.000***
Working memory	21.12 (3.83)	11 – 32	16.20 (4.12)	8 – 23	.000***
Processing speed	20.71 (4.41)	10 – 31	17.30 (5.22)	5 – 31	.000***

Note. Data are presented as absolute (and relative) frequencies or means (*SD*).
P-values are reported from a MANOVA for continuous variables and a X^2 test for categorical variables.
** $p < .01$.
*** $p < .001$.

discontinued their medication 24 h before the assessment (cf. Thompson, 2007). Results of the parental questionnaire asking for other developmental disorders in addition to ADHD revealed that some children with ADHD had co-occurring disorders of speech and language ($n = 3$), disorders of scholastic skills ($n = 2$), and other developmental disorders (e.g., delayed emotional development, $n = 4$). Parents of two children with ADHD reported a co-morbid developmental coordination disorder. No other co-occurring diagnoses with motor characteristics (e.g., tic disorders) were reported. Furthermore, no child with or without ADHD had to be excluded due to a potential intellectual impairment (IQ < 70), assessed with the German version of the Wechsler Intelligence Scale for Children fourth edition (WISC-IV; Petermann & Petermann, 2011). The ethics committee in Northwestern and Central Switzerland (EKNZ) approved the current study (Nr. 386/11). Parents gave written informed consent; children assented verbally. Previous research investigating similar relations between fine manual control and cognitive abilities showed moderate effect sizes with the smallest correlation being $r = .265$ (cf. Davis et al., 2011). A priori power analyses with G-Power 3.1, based on this correlation, assuming a power of .80, and significance levels of $p < .05$, revealed a minimum sample size of 141 children to detect a relation between two variables in a hierarchical regression with five predictors. Therefore, the present study is assumed to be adequately powered for computing these correlational analyses. The present study is also adequately powered for comparing motor and cognitive performance between the two groups (children with and without ADHD). As previous effect sizes of $\eta^2 = .10$ were found for differences in children's fine motor skills between children with and without ADHD (cf. Bünger, Urfer-Maurer, & Grob, 2019), another power analysis based on this effect size revealed a total sample size of 138 children, assuming a power of .80 and significance levels of $p < .05$.

2.2. Procedure and measures

Children were tested at the University with a battery of tasks including the Movement Assessment Battery for Children (M-ABC-2; Henderson, Sugden, & Barnett, 2007) and the WISC-IV (Petermann & Petermann, 2011). Age-standardized measures were chosen to ensure comparability between different-aged participants and across measurements. The M-ABC-2 measures general motor ability in children between 3;0 to 16;11 years based on performance in three motor subcomponents: manual dexterity, aiming and catching, and balance. The M-ABC-2 shows a high retest-reliability with coefficients between 0.73 and 0.84 and high inter-rater reliability with coefficients between .92 and 1.00 (cf. the M-ABC-2 manual; Henderson et al., 2007, p. 139). Given that the present study focused exclusively on fine motor skills (cf. van der Fels et al., 2015), only children's performance on the manual dexterity subcomponent was included which reflect typical measures of children's fine motor skills (e.g., Roebers et al., 2014). The manual dexterity tasks differ slightly for the two age bands of 7–10 years and 11−16 years and consist of three subtests: a one-handed posting task, a bimanual assembly task, and a trail-drawing task. The younger age group had to place pegs into a board, thread a lace, and draw a line through a trail; the older age group had to turn the pegs on the board, construct a triangle with nuts and bolts, and draw a line through a narrower trail. For the first two subtests, times of completion were measured; for the third subtest, errors were assessed. Scores of these subtests were added and standardized to compile an age-standardized score for fine motor skills ($M = 10$, $SD = 3$, range = 1–19).

Intelligence was measured with the standardized WISC-IV (Petermann & Petermann, 2011). This test is widely used and the internal consistency reliability coefficients range between 0.87 and 0.97 (cf. HAWIK-IV manual; Petermann & Petermann, 2011, p. 115). The full-scale IQ is measured based on four indices: (a) verbal comprehension (understanding and conceptualizing of verbal information); (b) perceptual reasoning (non-verbal, fluid reasoning and the understanding of visual information and solving abstract visual problems); (c) working memory (the ability to hold, organize, and manipulate verbal information); and (d) processing speed (the mental speed with which information is processed and nonverbal problems are solved; Groth-Marnat, 2009). For each of the ten core subtests of the WISC-IV, an age-standardized score is computed ($M = 10$, $SD = 3$, range = 1–19) and the respective subtest scores are added to compute the four index scores. Notably, responding to some subtests of the indices perceptual reasoning and processing speed index requires hand-eye coordination skills (e.g., Loh, Piek, & Barrett, 2011). Conversely, performances on the indices working memory and verbal comprehension can be evaluated independently from motor skills as their subtests do not include motor participation.

2.3. Statistical analysis

Analyses were performed using IBM SPSS 25. A multivariate analysis of variance (MANOVA) examined differences in the key variables (fine motor skills, intelligence, sex, maternal education, and age) between children with and without ADHD. To analyze the relation between fine motor skills and intelligence, five hierarchical regressions were computed, one for each dependent variable of intelligence (full-scale IQ, verbal comprehension, perceptual reasoning, working memory, processing speed). The independent variable fine motor skills was mean-centered to address the problem of multicollinearity when introducing an interaction term (Aiken & West, 1991). The control variables sex and maternal education were entered into the first step of the hierarchical regression. Since age-standardized values were examined for fine motor skills and intelligence, age was not again controlled for in the analyses. In the second step, the predictor variables fine motor skills and group (typically developing vs. ADHD) were added. Finally, in the third step, the interaction term of Fine motor skills × Group was included. A significant interaction term was followed up by separate regression analyses for each group. Due to the different sample sizes of typically developing children ($n = 139$) and children with ADHD ($n = 46$), two follow-up sensitivity analyses with same-sized samples were conducted: (a) matched for maternal education, sex, and age and (b) matched for full-scale IQ, sex, and age.

3. Results

Descriptive statistics of demographic variables, fine motor skills and intelligence of children with and without ADHD are provided in Table 1. The MANOVA showed a significant main effect of group, Wilks multivariate test, $F(1,183) = 12.76$, $p < .001$, $\eta^2 = 0.42$. The two groups differed significantly on every variable of interest. Children with ADHD were predominantly male, their mothers reported lower educational levels, and they showed lower fine motor skills and intelligence scores.

Hierarchical regression analyses for the combined sample are presented in Table 2. Analyses demonstrated significant associations between fine motor skills and full-scale IQ after accounting for effects of sex and maternal education ($\beta = .306$; $p < .001$). Furthermore, fine motor skills were specifically related to perceptual reasoning ($\beta = .327$; $p < .001$), processing speed ($\beta = .303$; $p < .001$), and working memory ($\beta = .185$; $p < .01$), whereas fine motor skills and verbal comprehension were not significantly related ($\beta = .121$; $p = .117$). Furthermore, results showed significant associations between group (typically developing vs. ADHD) and full-scale IQ ($\beta = .276$; $p < .001$), verbal comprehension ($\beta = .170$; $p < .05$), perceptual reasoning ($\beta = .196$; $p < .01$), and working memory ($\beta = .387$; $p < .001$), and a tendency for processing speed ($\beta = .146$; $p = .052$).[1] Overall, the hierarchical regression analyses for the combined sample demonstrated significant associations between fine motor skills and intelligence above and beyond effects of maternal education.[2] Moderated hierarchical regressions compared the strength of these associations between the groups. These analyses revealed significant interactions between fine motor skills and full-scale IQ ($\beta = -.206$, $p < .01$), perceptual reasoning ($\beta = -.205$, $p < .05$), and verbal comprehension ($\beta = -.240$, $p < .01$). No significant moderation resulted for processing speed ($\beta = -.091$, $p = .274$) nor working memory ($\beta = -.091$, $p = .250$).

Post-hoc hierarchical regression analyses were calculated separately by group for those dependent variables with a significant moderation effect (Table 3). Fine motor skills were more strongly related to full-scale IQ in children with ADHD ($\beta = .493$, $p < .001$) as compared to typically developing children ($\beta = .248$, $p < .01$; Fig. 1a). The same holds for the relation between fine motor skills and perceptual reasoning (typically developing children: $\beta = .254$, $p < .01$; children with ADHD: $\beta = .523$, $p < .001$; Fig. 1b). Furthermore, fine motor skills were significantly related to verbal comprehension ($\beta = .392$, $p < .01$) in children with ADHD, whereas this relation was non-significant for typically developing children ($\beta = .025$, $p = .773$; Fig. 1c).

4. Discussion

The present study examined the relations between fine motor skills and various aspects of intelligence in typically developing children and explored whether these associations were stronger for children with ADHD. Results indicated significant relations between children's fine motor skills and full-scale IQ, perceptual reasoning, working memory, and processing speed in the combined sample of children with and without ADHD, after accounting for sex, age, and maternal education. This speaks for a general association between cognitive and motor skills, with higher levels of fine motor skills being related to higher intelligence scores. Given that the present study found links between fine motor skills and intelligence above age effects (e.g., Pagani, Fitzpatrick, Archambault, & Janosz, 2010; Suggate & Stoeger, 2014), a maturational hypothesis seems unlikely. Such a hypothesis implies that more advanced and older children demonstrate higher performance on all types of tasks (cf. Cameron et al., 2012). The current findings do also not provide evidence for the socioeconomic hypothesis which states that relations between fine motor skills and intelligence may reflect differences in the socioeconomic background (cf. Cameron et al., 2012). Specifically, it is assumed that achievement gaps are found in children with disadvantages in family, parental, and societal emphasis due to fewer opportunities to enhance their attentional skills and improve fine motor skills as compared to more advantaged children (Grissmer et al., 2010). Given that the present findings hold after accounting for maternal education as well as when matching for maternal education (see footnote [2]), the results do not seem to support claims of the socioeconomic hypothesis.

Whereas fluid aspects of intelligence such as perceptual reasoning, processing speed and working memory were related to fine

[1] Based on results from previous research (van der Fels et al., 2015), the present study has focused exclusively on the subcomponent manual dexterity and its relation to children's intelligence. However, to enable comparability, two post-hoc hierarchical regressions with the subcomponents aiming and catching, and balance were calculated. Analyses revealed non-significant relations between children's ball skills and intelligence and its four indices, as well as no significant interactions (all βs $< .145$; all ps $> .05$). Similarly, associations between balance skills and intelligence were non-significant (except for perceptual reasoning), as well as the interaction terms (βs $< .125$; ps $> .05$). These results are in line with previous research stating that fine motor skills seem to relate more strongly to cognition as compared to gross motor skills.

[2] Two sensitivity analyses revealed that the pattern of results remained widely similar when the total sample of children with ADHD ($n = 46$; $M_{age} = 10.2$; 9 girls) was matched with a subsample of typically developing children (it should be noted that these analyses were not adequately powered given the power analyses). In the first analysis, children with ADHD and typically developing children ($n = 46$; $M_{age} = 10.7$; 9 girls) were matched for maternal education, sex, and age. The interaction of Fine motor skills × Group (TD vs. ADHD) remained significant for verbal comprehension ($\beta = -.206$, $p = .049$). Although, interactions for full scale IQ ($\beta = -.170$, $p = .064$) and perceptual reasoning ($\beta = -.166$, $p = .077$) shifted to tendencies, the beta values remained widely comparable to results with the full sample. The second analysis tested whether the interactions could be explained by differences in children's cognitive outcome. Subsequently, typically developing children ($n = 46$; $M_{age} = 9.7$; 9 girls) were matched for full-scale IQ, sex, and age with children diagnosed with ADHD. Results revealed significant associations between fine motor skills and all five intelligence variables (βs $> .226$, ps $< .026$). Group (TD vs. ADHD) was no longer significantly related with intelligence (except for working memory) indicating that the matching procedure was successful. Importantly, the interaction of Fine motor skills × Group (TD vs. ADHD) reached significance (βs $< -.227$ ps $< .05$) for all intelligence variables except for working memory. These follow-up analyses show the robustness of the associations between fine motor skills and intelligence.

Table 2
Hierarchical regression analyses with fine motor skills and group (typically developing children and children with attention deficit hyperactivity disorder) predicting intelligence indices ($N = 185$).

Predictors	Intelligence indices				
	Full-scale IQ	Perceptual reasoning	Verbal comprehension	Working memory	Processing speed
Step 1					
Sex	−.063	−.055	.056	−.138+	−.118
Maternal education	.323***	.280***	.275***	.194**	.220**
R^2 of total model	.117***	.088***	.072**	.068**	.074**
Adjusted R^2 of total model	.108***	.078***	.062**	.058**	.064**
Step 2					
Sex	.070	.070	.119	−.021	−.008
Maternal education	.226**	.203**	.220**	.074	.159*
Fine motor skills	.306***	.327***	.121	.185**	.303***
Group (TD vs. ADHD)	.276***	.196**	.170*	.387***	.146+
ΔR^2 step 2	.197***	.165***	.050**	.201***	.126***
R^2 of total model	.314***	.253***	.122**	.269***	.200***
Adjusted R^2 of total model	.299***	.237***	.102**	.253***	.182***
Step 3					
Sex	.060	.061	.108	−.025	−.012
Maternal education	.215**	.193**	.208**	.070	.154*
Fine motor skills	.427***	.448***	.262**	.239**	.356***
Group (TD vs. ADHD)	.195**	.155	.076	.351***	.111
Fine motor skills x group (TD vs. ADHS)	−.206**	−.205*	−.240**	−.091	−.091
ΔR^2 step 3	.027**	.027*	.037**	.005	.005
R^2 of total model	.342**	.280*	.159**	.275***	.205***
Adjusted R^2 of total model	.323**	.260*	.136**	.254***	.183***

Note. TD = typically developing children. ADHD = children with attention deficit hyperactivity disorder.
Coefficients are standardized regression coefficients if not otherwise indicated.
Step 1: model with control variables predicting intelligence. Step 2: model with fine motor skills and group (TD vs. ADHD) as predictors of intelligence, controlled for variables entered in step 1. Step 3: model with the interaction term fine motor skills x group (TD vs. ADHD) as predictor of intelligence, controlled for variables entered in step 1 and 2. Sex: -1 = female; +1 = male. Group: -1 = ADHD; +1 = TD.
+ $p < .06$.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 3
Hierarchical regression analyses with fine motor skills predicting intelligence separated for typically developing children and children with attention deficit hyperactivity disorder.

Predictor	Typically developing children ($n = 139$)			Children with ADHD ($n = 46$)		
	Full-scale IQ	Perceptual reasoning	Verbal comprehension	Full-scale IQ	Perceptual reasoning	Verbal comprehension
Step 1						
Sex	.026	.005	.167+	−.074	−.035	−.166
Maternal education	.193**	.178**	.171*	.331**	.264+	.310*
R^2 of total model	.036+	.031	.049*	.127+	.075	.149*
Adjusted R^2 of total model	.022+	.017	.035*	.087+	.032	.110*
Step 2						
Sex	.091	.072	.173+	.001	.045	−.106
Maternal education	.202*	.187**	.172*	.293**	.224+	.280*
Fine motor skills	.248**	.254**	.025	.493***	.523***	.392**
ΔR^2 step 2	.057**	.060**	.001	.235***	.264***	.148**
R^2 of total model	.094**	.091**	.049	.362***	.339***	.297**
Adjusted R^2 of total model	0.74**	.071**	.028	.316***	.292***	.247**

Note. TD = typically developing children. ADHD = children with attention deficit hyperactivity disorder.
Coefficients are standardized regression coefficients if not otherwise indicated.
Step 1: model with the control variables predicting intelligence. Step 2: model with fine motor skills as predictor of intelligence, controlled for variables entered in step 1. Sex: -1 = female; +1 = male.
+ $p < .10$.
* $p < .05$.
** $p < .01$.
*** $p < .001$.

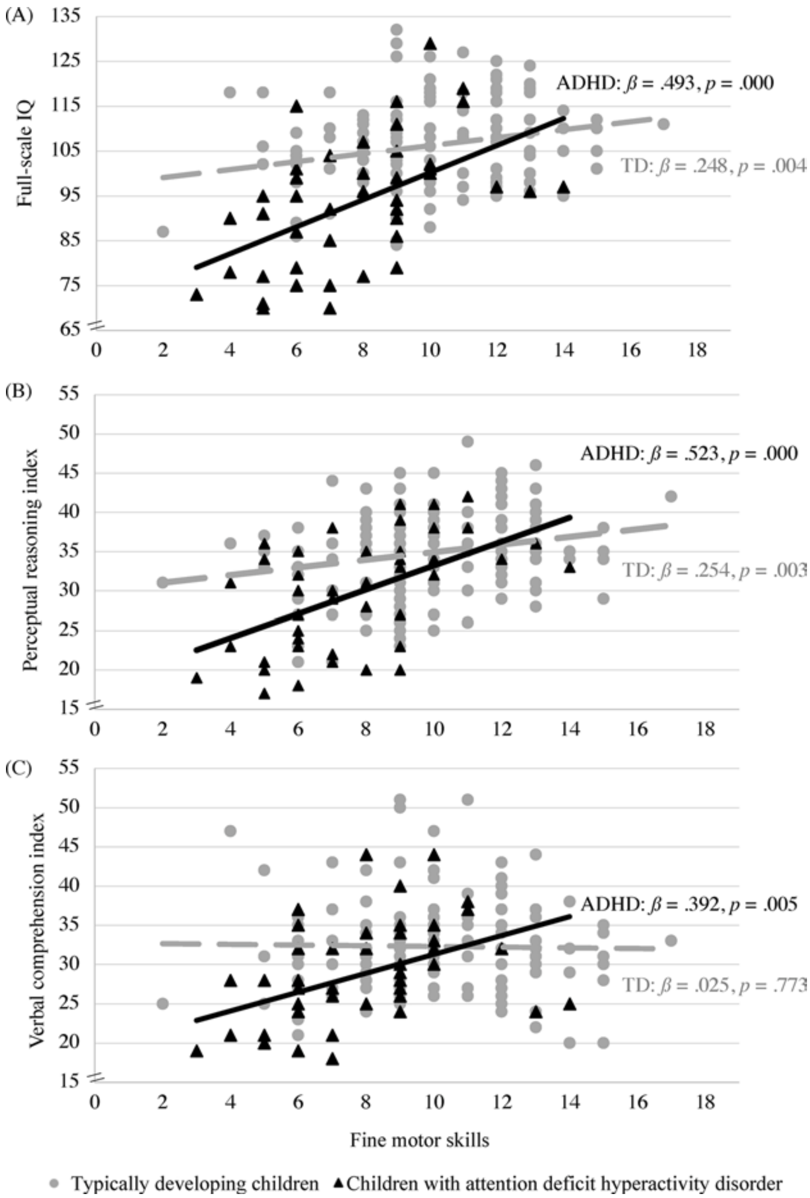

Fig. 1. Relation between fine motor skills and (**a**) full-scale IQ, (**b**) perceptual reasoning and (**c**) verbal comprehension for typically developing children (TD) and children with attention deficit hyperactivity disorder (ADHD). Standardized regression coefficients (*β*) and *p* values are presented next to the slopes.

motor skills in the combined sample, there was no significant relation between children's fine motor skills and verbal comprehension, reflecting crystallized aspects of intelligence. Therefore, it seems that aspects of fluid intelligence may be more closely related to fine motor skills as compared to aspects of crystallized intelligence, which is in line with previous conclusions (van der Fels et al., 2015). Interestingly, the present moderation analyses extend this conclusion with fine motor skills and verbal comprehension not being significantly related in typically developing children. This result contrasts some previous studies demonstrating that fine motor skills were related to language and vocabulary in typically developing children between the ages of 3–6 years (Dellatolas et al., 2003; Pagani et al., 2010). However, the result is in line with the study from Wassenberg et al. (2005), which indicated no significant relation between vocabulary and visuo-motor integration which is a construct related to fine motor skills.

Furthermore, the current findings implied that fine motor skills were related to language in children with ADHD which supports previous findings (e.g., Cameron et al., 2012). Even though explanations for this result remain speculative with the data at hand, significant findings may be explained according to the embodied cognition theories and with the nimble hands nimble minds hypothesis, which supports the idea of learning through fine motor controlled activities (Suggate & Stoeger, 2014). Additionally, some may refer to the higher variance in the intelligence scores of children with ADHD as a greater possibility to detect shared variance between motor and cognitive skills. However, when matching the two groups so that they do not significantly differ in full-scale IQ, the relation between fine motor skills and intelligence as well as the interactions terms remained significant (see footnote [2]). This analysis supports the interpretation that the significant interactions in the full sample are not the result of cognitive differences between these two groups. More research is needed to explore the mechanisms underlying these different relations. Nevertheless, the present study provides first evidence that motor-cognition links may be more prominent in school-aged children with ADHD as compared to same-aged typically developing children.

In addition to verbal comprehension, there were also significant interactions for full-scale IQ and perceptual reasoning which indicated stronger relations for children with ADHD as compared to typically developing children. The pattern of findings implies that children with ADHD did not show stronger relations between all indices of intelligence and fine motor skills, suggesting specific patterns and differences between the groups. However, overall, the findings demonstrated stronger relations between fine motor skills and full-scale IQ in children with ADHD as compared to typically developing children which is in line with previous research (Dyck et al., 2006; Houwen et al., 2016). Whereas this may reflect an unusual dependence among neurocognitive processes in children with ADHD, it may also be the case that fine motor performance requires more cognitive control in this clinical sample and is already more automatized in same-aged, typically developing children (cf. Ackerman, 1988). The current study cannot disentangle between these explanations; thus, future research with preferably neuroimaging techniques may be helpful to assess the underlying mechanisms of these differential patterns between children with and without ADHD.

Although there are motor components included in several subtests of the WISC-IV (e.g., Loh et al., 2011), it is unlikely that this is the main influence of this relations. Whereas answering subtests of perceptual reasoning and processing speed requires hand-eye coordination skills, working memory and verbal comprehension do not. Given the significant associations between fine motor skills and working memory as well as verbal comprehension, it seems that fine motor skills and intelligence are connected independently from motor requirements in these cognitive tasks.

The present findings may hold important implications for treating children with ADHD. When diagnosing ADHD according to the criteria of the DSM-IV or ICD-10, the symptoms inattention, hyperactivity, and impulsivity are considered whereas motor abilities are typically not included. Consequently, motor skills are often not acknowledged in ADHD intervention programs (e.g., Fliers et al., 2010). The results of the current study, demonstrating significant relations between fine motor skills and intelligence, advocate the consideration of motor abilities and support multidimensional approaches as for example motor-cognitive interventions. Such interventions focus additionally on children's motor problems and have been found to increase children's quality of life (Fliers et al., 2010).

Even though the mechanisms of the relation between fine motor skills and intelligence remain unclear and need further research, the current study extended previous studies and contributed to the understanding of this relation in samples of typical and clinical development. Notably, the usage of a large, homogenous sample of children diagnosed with ADHD enabled to extend previous studies using very heterogenous samples (Houwen et al., 2016; Martin et al., 2010) and allows specific conclusions for the developmental disability of ADHD. Additionally, the large sample of same-aged typically developing children allowed for replicating previous findings and extending this research to an older age range while at the same time serving as a control group to compare results between typical and clinical development. Another strength of the present study refers to the statistical approach which allowed to account for a number of influential variables (age, sex, and maternal education; Aiken & West, 1991). Finally, the present study used standardized measurement instruments of fine motor skills and intelligence which have been proven to be reliable and valid (Henderson et al., 2007; Petermann & Petermann, 2011).

The different sample sizes of children with and without ADHD can be seen as a limitation. However, as the pattern of results was widely similar when using same-sized samples matched for sex, age, and maternal education (see footnote [2]), this issue is not considered as problematic. Another possible limitation concerns the significant mean differences and variances of intelligence and fine motor skills between the groups, which largely reflect the symptoms of ADHD and underline the representativity of our sample of children with ADHD. However, since both groups show sufficient variance in our measures, we do not assume that these differences are constraining our correlational approach. Furthermore, our sample of children with ADHD did not allow for separating among different subtypes of ADHD. Such a differentiation may be useful given that previous research showed that children with ADHD in the subtypes "predominantly inattentive" and the combined type had significantly poorer fine motor skills than typically developing children, while children in the subtype "impulsive/hyperactive" did not significantly differ from controls (Egeland, Ueland, & Johansen, 2012; Pitcher, Piek, & Hay, 2003). Future research should investigate whether differentiating between these subtypes influences the relation between fine motor skills and intelligence. Additionally, the children with ADHD with medical treatment discontinued their medication prior to the study which could have affected their performance. While this approach enabled to measure children's baseline performance without the influence of medication, future studies should corroborate these findings examining children with ADHD who continued their medication (Kaiser et al., 2015). Moreover, the correlative, cross-sectional design of the present study does not allow for testing the direction of the association between fine motor skills and intelligence. Future studies may examine relations between fine motor skills and intelligence using a longitudinal approach with cross-lagged model design. Finally, previous research has typically used a M-ABC-2 score below the 16th percentile to identify children with DCD (e.g., Alloway & Temple, 2007). According to this criterion, 15 children with ADHD (32.6 %) of the current sample may be considered for a DCD diagnosis. Consequently, the significant relation between fine motor skills and intelligence may not be limited to the clinical sample of children with ADHD and further research is needed to examine this relationship in other clinical samples.

5. Conclusion

The current study investigated relations between fine motor skills and several aspects of intelligence in typically developing children and children with ADHD aged 7–13 years. Results suggest a close relation between fine motor skills and intelligence in children with and without ADHD. These results add to previous findings suggesting such relations in typically developing children at the age of kindergarten (e.g., Cameron et al., 2012) and proposes that fine motor skills continue to be an indicator for cognitive skills across childhood until early adolescence. Furthermore, the current study highlights stronger associations between fine motor abilities and intelligence in children with ADHD – a developmental disorder characterized by attention deficits and being less perceived for motor difficulties – as compared to typically developing children. The present results lend support for implementing motor-cognitive interventions in treating children with ADHD. Overall, the present findings are in line with an embodied cognition perspective, demonstrating close connections between motor and cognitive skills in typical and ADHD samples.

Authorship statement

A. Grob and S. Lemola substantially contributed to the conception and design of the study. S. Lemola substantially contributed to the acquisition of data. W. Möhring and S. Klupp substantially contributed to the analyses of the present manuscript. All authors contributed to the interpretation of data. S. Klupp drafted the manuscript. All authors critically revised the article and approved the final version to be published.

Declaration of Competing Interest

The authors report no declarations of interest.

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