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Review article

The link between motor and cognitive development in children born preterm and/or with low birth weight: A review of current evidence

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A R T I C L E I N F O

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A B S T R A C T

The current review focuses on evidence for a link between early motor development and later cognitive skills in children born preterm or with Low Birth Weight (LBW). Studies with term born children consistently show such a link. Motor and cognitive impairments or delays are often seen in children born preterm or with LBW throughout childhood and studies have established a cross-sectional association between the two. However, it is not yet clear if, and if so, how, motor and cognitive skills are longitudinally interrelated in these children. Longitudinal studies with this population including measures of motor development during the first year of life and cognitive measures at later measurement points were included. The 17 studies included usually show a link between level and/or quality of motor development during the first year of life and later cognitive skills in children born preterm and/or with LBW. However, given the small number of studies, and a possible effect of early interaction between motor and cognitive skills affecting this relation, more work is clearly needed.

1. Introduction

In recent years a growing body of theories and their underlying empirical evidence (e.g., Hockema and Smith, 2009; Iverson, 2010; Oudgenoeg-Paz et al., 2015; Piek et al., 2004; Rosenbaum, 2005; Soska et al., 2010) argue for a link between early motor skills and later cognitive development. This work has mainly been done with term born, typically developing children. The current paper reviews the evidence pertaining to such a link in the development of children born preterm and/or with a Low Birth Weight [LBW]. Major advances in medical treatment of infants born preterm (Gestational Age [GA] < 37 weeks) and/or those with a LBW (less than 2500 g) have led to an increase in the survival rate of these infants (Ruegger et al., 2012; Stoelhorst et al., 2005). These children are at risk for developmental delays later in life (e.g., Aylward, 2005; Guerra et al., 2014; Sansavini et al., 2014). Two main areas of delay are motor and cognitive functioning (For reviews see: de Kieviet et al., 2009; Mulder et al., 2009; Van de Weijer-Bergsma et al., 2008) and multiple studies have reported cross-sectional correlations between motor and cognitive impairments in children born preterm or LBW (e.g., Domellöf et al., 2013; Marlow et al., 2007; Van Hus et al., 2014). However, evidence about longitudinal relations between motor and cognitive development in these children is still rather scarce. The current paper will review evidence for a longitudinal link between motor and cognitive development during early childhood in children born preterm and/or with LBW. Establishing such a longitudinal link in these children will enable researchers to come a step closer to understanding the fine dynamics of the (often delayed or impaired) development of these children. Moreover, insights into such a link can serve to inform early diagnosis and intervention programmes.

One of the theoretical approaches particularly relevant for studying child development is the embodied cognition approach, which proposes a framework in which motor and cognitive development are strongly linked. This framework is in many ways rooted in the ecological psychology approach to perception and action. According to this approach, children develop cognitive skills through an ongoing interaction with their environment. As children (physically) explore their environment they learn about the affordances in their environment. The affordances are possibilities for action which are dependent on both the characteristics of the child (e.g., arm length, reaching skill, postural control skills) and on the characteristics of the (objects in) the environment (Gibson, 1979). While exploring, children both receive information from their environment and act on their environment in a way that generates new information to be perceived. These ongoing perception-action cycles enable children to learn about the world around them and

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develop (among other things) their cognitive skills (Gibson, 1988; Smith and Gasser, 2005; Thelen and Smith, 1994). Motor development changes children's abilities to act in their environment, the affordances of their environment and the perceptual information children's actions generate. In fact, motor development sets a developmental cascade in motion. By enabling children to generate and perceive new information, motor development forms a major factor causing perturbations in the developing system, setting the stage for the development of (higher order) cognitive skills (Gibson and Pick, 2000; Smith et al., 1999; Smith and Gasser, 2005; Thelen and Smith, 1994).

1.1. Evidence from term born children

Inspired by this theoretical view, recent work conducted with typically developing children has demonstrated that motor development indeed propels cognitive development on many levels. For example, studies show that the attainment of self-produced locomotion is related to cognitive advances such as success on spatial search tasks (Berger, 2010; for a review see Campos et al., 2000; Clearfield, 2004) and mental rotation tasks (for a review see: Mulder et al., 2017). Other studies link action with objects to cognitive skills such as 3D perception (Soska et al., 2010), mental rotation (Möhring and Frick, 2013), and better visuospatial memory at age four and six years (Oudgenoeg-Paz et al., 2014). Initial investigations also suggest some insights in possible mediators of these links, suggesting that, in line with the theoretical views discussed, motor development enables children to interact differently with the environment, thus creating new learning opportunities which aid children in constructing their cognitive skills (Karasik et al., 2011; Oudgenoeg-Paz et al., 2014; Oudgenoeg-Paz et al., 2015; Soska et al., 2010; Walle and Campos, 2014).

1.2. Evidence from children born preterm and/or LBW

Children born very preterm (< 32 weeks GA) or with LBW very often show persistent motor impairment or delays throughout childhood (de Kieviet et al., 2009; Hediger et al., 2002; Johnson et al., 2015). Areas of impairment are seen across the range in gross motor, fine motor and perceptual-motor skills (Bos et al., 2013; De Rose et al., 2013; Månsson and Stjernqvist, 2014). Some cross-sectional evidence suggests that these children do catch up on their initial motor delay (as measured by standard tests such as the Bayley Scales of Infant Development [BSID]), although they continue to lag behind typically developing children during primary school and early adolescence in motor skills (as measured by standard tests such as the Movement Assessment Battery for Children [MABC]) (de Kieviet et al., 2009). However, longitudinal evidence reveals that there is large variability in the developmental trajectories of motor development of these children and that definitely not all children catch up (Janssen et al., 2016; Janssen et al., 2011).

A second domain where infants born preterm or with LBW exhibit difficulties is the cognitive domain (Johnson et al., 2015). Empirical studies reveal that these children show deficits or developmental delays in attention, including selective attention and sustained attention. These problems are present already at a very young age and persist into childhood for children born at a low GA (below 26 weeks), while some of the children with higher GA do seem to catch up in this domain (for reviews see: Mulder et al., 2009; Van de Weijer-Bergsma et al., 2008). Multiple studies reveal that these children perform worse than children born at term on executive functions tasks and specifically on tasks measuring visuospatial working memory (e.g., Caravale et al., 2005; Mulder et al., 2009; Vicari et al., 2004). These effects are also visible during adolescence (for a review see: Mulder et al., 2009). Children born preterm or with LBW are more likely to receive therapeutic and educational interventions (Bettge et al., 2014; Reuner et al., 2009). Moreover, studies conducted with young adults who were born preterm or with LBW reveal that they still show impairments in executive function tasks involving response inhibition and mental flexibility (Nosarti et al., 2007). Furthermore, young adults born preterm often have lower educational level, lower income, and are more likely to receive social security benefits (Lemola, 2015; Lindström et al., 2007; Moster et al., 2008). Thus, it is clear that children born preterm or with LBW often show impairments in both the motor and the cognitive domains already at a young age and this co-occurrence of difficulties lasts into childhood. However, while co-occurrence of difficulties is common, motor difficulties do also occur independently of cognitive or behavioural difficulties (Foulder-Hughes and Cooke, 2003; Moreira et al., 2014). Moreover, it is not yet clear if, and if so, how, these two areas of difficulty are also interrelated over time. In other words, are the children who suffer from delayed or abnormal motor development early in life also the children who face difficulties in the cognitive domain later on?

1.3. Current review

According to the embodied cognition approach, cognitive difficulties observed in children born preterm and/or with LBW are probably the result of a developmental cascade originating in early development. This theory suggests that due to impaired (or severely delayed) motor skills, these children might not always be able to explore their environment and interact with it as other children do. These initial deficits and delays ultimately might lead, through a cascade of effects, to cognitive delays later in life. If this is the case, than this situated nature of cognition implies that the links between early motor delays and impairments and later cognitive impairments are specific and not all motor skills will be related to all cognitive skills. Moreover, other factors may also influence this cascade, and weaken or strengthen the link. On the other hand, other theories argue that the co-occurrence of deficits in multiple domains in children born preterm or with LBW is due to a general impairment (Wolke and Meyer, 1999; Wolke et al., 2008). This general impairment might be due to disruption of global brain development, or subtle white matter alterations (de Kieviet et al., 2014; de Vries et al., 2015; Kapellou et al., 2006). These subtle alterations may be related to subsequent altered brain development, which, in turn, is correlated with dysfunction in a wide range of domains, including general intelligence, attention, executive functions and motor skills (de Vries et al., 2015; Lemola, 2015). Such a general impairment hypothesis predicts that these children would be impaired to some extent in all areas of cognitive functioning. The severity of the impairment may differ according to the severity of brain damage. Thus, from this perspective, early motor impairments are expected to be linked to all aspects of later cognitive impairment due to their shared source. Longitudinal relation between motor and cognitive development could then be explained by early cross-sectional relations between these domains and by the underlying brain damage.

In this review we aim to discuss current work on longitudinal links between motor and cognitive development in children born preterm and/or with LBW. Given the recent impulse in research on these questions in typically developing children, and given the implications the answers to these questions might have for clinical practice, it is important to provide a picture of the current state of research in this field.

2. Method

The current review is a narrative review. This is a method for summarizing and synthesizing relevant literature that aims to provide understanding of the current state of knowledge in the field and pointing out directions for future research (Cronin et al., 2008). Given the limited number of studies addressing the questions which are the focus of this review, a comprehensive systematic review might still be premature (Haddaway et al., 2015). Using rigorous selection methods and excluding studies based on their design and quality might lead to loss of too much information in a field where information is already scarce (Arksey and O'Malley, 2005). Therefore it was chosen to conduct a narrative review rather than a systematic review.

The process followed for searching and identifying relevant literature was conducted in a systematic manner as suggested in the literature (e.g., Arksey and O'Malley, 2005; Cronin et al., 2008; Haddaway et al., 2015). First inclusion and exclusion criteria were specified and the search procedure was designed and agreed upon by the first and third author. Inclusion criteria were: longitudinal studies in children born preterm (GA $<$ 37 weeks) or with LBW ($<$ 2500 g) testing relations between motor skills measured during the first year of life and cognitive skills at later measurement points. Studies were included if motor skills were assessed using specific measures (e.g., attainment of specific milestones), general measures (e.g., assessment of motor development using the BSID) or measures of motor behaviour (e.g., measures of observations of motor behaviour such as assessment of General Movement). Similarly, included studies used measures of cognitive skills that were either specific (e.g., test of spatial working memory) or general (e.g., mental scale of the BSID). Exclusion criteria were: outcome result involving only combined results of general assessments such as the BSID without report of the results of the motor and cognitive scales separately. These papers were excluded as this report does not enable a distinction between the relation with cognitive and motor development.

The search was limited to peer-reviewed papers published in English between January 1 st 1990 and April 1 st 2017. Initial search was conducted in PsychInfo, PubMed and Web of Science. Additionally, complementary search was conducted in Google Scholar, by going over the first 100 results provided. This can be considered sufficient as Google Scholar provides a large amount of irrelevant results and does not seem to have a large added value when searching for peer-reviewed papers that are also indexed in search engines such as PubMed (see for example Falagas et al., 2008; Shultz et al., 2007). Search terms used were (1) ‘motor development’, ‘motor skills’, ‘postural control’ or ‘motor milestones’ in combination with (2) ‘cognition’, ‘cognitive skills’ or ‘academic skills’, and (3) ‘preterm’ or ‘low birth weight’.

First selection of the papers was made based on the titles. Next, the abstracts of the selected papers were read to select relevant papers. Finally, the full text of the selected articles was read. Papers were included in the review based on their full text. The first author conducted the search and selected the studies for inclusion. In case of doubts the second and third authors were consulted. In the next stage the relevant information from the studies was extracted and charted in Excel by the first author. This information included: authors, year of publication, study population (inclusion and exclusion criteria if these were specified), study design, outcome measures and ages at which they were measured, results regarding longitudinal link between motor outcomes (measured between age 0 and 12 months) and cognitive outcomes (measured at a later time point) and the use of control variables.

In Table 1, the main characteristics and results of the studies included in this review are summarized. As can be seen from Table 1, 17 studies met the inclusion criteria and were included in the review. In the following sections we discuss these studies in detail. The included papers were divided in two groups: longitudinal studies into the link between level of motor development in the first years of life and later cognitive measures and longitudinal studies on the link between the quality of general movement and postural control in the first years of life and later cognitive outcomes. In our review of the evidence we will discuss the evidence according to this division, before moving on to a general discussion and an integrative conclusion.

3. Results

3.1. Level of motor development

We found five studies that tested the direct link between motor and cognitive development in children born preterm or with LBW, in a similar way as the studies done with term born, typically developing children. All these studies used general assessments of motor and cognitive level rather than specific aspects of motor or cognitive functioning. In a study of children with Extremely LBW ($<$ 1000 g) and a GA between 23 and 24 weeks, lower scores on a standard motor assessment including tests of gross and fine motor function, neurological status, patterns of movement, postural development and motor responses to sensory input, predicted lower scores on an IQ assessment at age 4 years (using the Developmental Quotient [DQ] out of the Griffith Mental Developmental Scale). The same strong relations remained when children with Cerebral Palsy (CP) were excluded (Burns et al., 2004). A second study examined the academic attainment (i.e., grade retention or attending special education) and IQ scores of 10 years old children with GA less than 32 weeks in relation to scores on the BSID at ages 12, 24 and 30 months. Children who displayed poor academic attainment scored lower on the motor scale already at age 12 months (and also at ages 24 and 30 months). Lower scores on the motor scale also predicted lower scores on the Wechsler Intelligence Scale for Children (WISC) (Van Baar et al., 2006). In contrast, Howe et al. (2016) showed that the motor scale of the BSID as measured at age 12 months, did not predict total WISC scores at age 5 years. However, infants scores on the Alberta Infant Motor Scales (AIMS) at age 12 months, did predict WISC scores at age 5 years, even when controlling for level of cognitive development at age 12 months (as measured by the BSID). An additional study using the AIMS showed that AIMS scores at age 4 months predict scores on the Mental Developmental Index (MDI) of the BSID at age 18 months. Additional assessment using the Movement Assessment of Infants (MAI) at age 4 months showed similar relations with MDI scores at age 18 months (Lefebvre et al., 2016). The last study we found showed that level of motor development and quality of motor performance as measured by a structured observation, at age 10 months post-term, predicted children's performance on the BSID at age 2.5 years post-term. When gender and GA were controlled for, the associations were only present for level of motor development and only for boys and children with a low GA (Montgomery et al., 2014). This last study included both level of motor development as well as quality of movement as predictors. We included it in the section concerning level of motor development as level of motor development was the stronger predictor in this study.

Taken together, these studies show that when measured with general standard assessments, children who fall behind in motor development early in life also fall behind in cognitive functioning at later ages (at least up to age 10 years). This relation is found consistently when different assessment methods are used for both motor and cognitive development. However, the number of studies is very small and the evidence concerning the predictive validity of the motor scores on the BSID at age 12 months for later cognitive development are conflicting. Moreover, as children born preterm and/or LBW show motor and cognitive delays already at an early age, it is possible that the longitudinal links between motor and cognitive development are confounded by the early cross-sectional relations between these domains. It is therefore important to control for level of cognitive development early in life when testing these relations. Only the study by Howe et al. (2016) controlled for early cognitive development and showed that the effect of early motor development on cognitive development at age 5 years remained significant. Thus, while these studies suggest that in children born preterm and/or LBW early level of motor development is related to later cognitive development, this conclusion has to be drawn with caution, as more evidence is still needed to replicate current findings and exclude possible confounds such as early level of cognitive development.

3.2. Motor behaviour

Given the small number of studies focussing on level of motor

Table 1
Main characteristics of studies included in the review.

Study (first author)	Participants	Exclusion/inclusion criteria of the study	Measures and age of measurement	Study design	Statistical test and effect size
Beccaria et al. (2012)	$N = 76$ M GA = 29.47 M birthweight = 1182 g Range is not reported.	**Inclusion**: GA < 32 weeks and/or Birth weight < 1500 g **Exclusion**: CP	**Motor**: Quality of GM **Age**: 1 and 3 months post term **Cognitive**: Griffiths Scales of Mental Development **Age**: 2 years.	Longitudinal, prospective	T test showed that the mean DQ on Griffith's scale was lower for infants with poor ($n = 20$) in comparison to normal GM repertoire ($n = 56$) at age 1 month ($d = 0.97$). This difference was also significant in an ANOVA controlling for other factors (no statistics reported). GM quality at age 3 months was not related to the DQ
Breeman et al. (2017)	$N = 260$ No further details about the participants' GA and birth weight are reported.	**Inclusion:** GA < 32 and/or birth weight < 1500 g No exclusion criteria are reported	**Motor:** The quantity and quality of mobility (slightly/greatly reduced/increased) were assessed daily at the NICU. **Cognitive:** WISC adults version. **Age:** 26 years	Prospective population study	Multiple regression analysis with background variables, measures of neonatal morbidity, neonatal treatment and early social environment has shown that quality of mobility retained a unique effect on IQ at age 26 years ($\|b\| = 0.27$, R^2 of the total model = 0.38).
Bruggink et al. (2010)	$N = 60$ Range GA 25–33 (median = 30 weeks) Range birthweight 595–1800 g (median = 1130) (no means reported)	**Inclusion**: GA < 34 weeks **Exclusion**: Conditions that might interfere with normal neurologic development and CP	**Motor:** Quality of GM Quality of motor repertoire **Age:** 1,2 weeks after birth and at weekly intervals until discharge, term age, ages 3 and 8 weeks (quality of GM). Between 11 and 17 weeks (quality of motor repertoire) **Cognitive:** WISC, school performance **Age:** 7–11 years	Prospective cohort study	Logistic regression has shown that a low quality of GM up to 8 weeks post term predicted low IQ scores (< 85) and school performance when controlling for background variables. Odds ratio for IQ = 4.9, and for school performance = 3.4. The model explained 22.4% of the variance in IQ and 10.6% of the variance in school performance. There was no relation found between GM quality at 11 and 17 weeks and IQ at school age.
Burns et al. (2004)	$N = 132$ Range GA 24–34 ($M = 26.5$, $SD = 1.6$) Birthweight < 1000 g ($M = 797$, $SD = 128$)	**Inclusion**: Birthweight < 1000 g No exclusion criteria are reported.	**Motor:** Neurosensory motor developmental assessment (NMDS) **Age:** 12 months **Cognitive:** McCarthy Scales of Children's Abilities **Age:** 4 years	Retrospective cohort study	The NMDS yields classification of children in four groups based on motor functioning. Multiple regression analysis was conducted with the classification on the NMDS as predictors of McCarthy's scale (normal classification being the reference group). Unstandardized regression coefficiets and 95% confidence intervals are reported: minimal motor problems = 10.0 (15.3, 4.7), mild motor problems = 4.3 (11.1, 2.5), moderate to severe motor problems = 23.7 (31.7,15.7). No effect sizes are reported. At 12 months, the NMDS was also cross-sectionally related to the DQ.
Butcher et al. (2009)	$N = 65$ Range GA 26–34 ($M = 29.9$, SD = 1.83) Range birthweight 595–1800 g ($M = 1196$, $SD = 289$)	**Inclusion:** Born preterm and belonged to a group of children who had participated in earlier investigations of associations between spontaneous movement quality and development **Exclusion**: Severe CP precluding valid intelligence measurements	**Motor:** Quality of GM **Age:** 11–16 weeks **Cognitive:** Four verbal subscales and three performance subscales of the WISC-III **Age:** Ages 7–11 years	Longitudinal, prospective	In a multiple regression analysis, after controlling for the parents' education and the child's age and attention problems, quality of GM significantly predicted the total IQ score ($\|\beta\| = 0.35$, Adjusted $R^2 = 0.296$). Similar results were obtained for the WISC III subscales. Neurological status at age 7–11 years did

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Table 1 *(continued)*

Study (first author)	Participants	Exclusion/inclusion criteria of the study	Measures and age of measurement	Study design	Statistical test and effect size
					not mediate this relation. Similar results were obtained also when children suffering from mild CP were excluded. Further analysis revealed that specifically the frequency of abnormal vs. normal postural patterns predicted IQ scores ($\lvert\beta\rvert = 0.31$).
De Bock et al. (2017)	$N = 122$	**Inclusion**: GA < 33, participating in follow-up programme at a non-academic outpatient centre	**Motor:** Quality of GM **Age:** 1 or 3 months (primarily 1 month, only when lacking 3 months assessment was used). **Cognitive:** BSID **Age:** 2 years	Prospective cohort study	Linear regression showed that abnormal GM at age 1 or 3 months predicted a score of 12.0 index points lower on the MDI, while controlling for background variables (95% CI: 23.2, 0.86, effect size: $\Omega^2 = 0.025$).
Fj & rtoft et al. (2013)	$N = 40$ (31 with birth weight < 1500, 34 born preterm) *M* GA = 29.3 (*SD* = 5.3) *M* birthweight = 1373 g (*SD* = 999) Ranges were not reported	**Inclusion**: Children admitted to the NICU and then referred to physiotherapy. Additional 9 children included were not preterm but high risk children (due to intracerebral abscess, neonatal encephalopathy and neonatal seicures) and referred to physiotherapy. **Exclusion**: Follow up conducted in a different hospital, complications during the stay at the NICU and birth weight < 1000 g.	**Motor:** Quality of fidgety movements and of current motor repertoire (these are specific aspects of GM) **Age:** On average 14 weeks post-term **Cognitive:** WISC III **Age:** 10 years	Prospective cohort study	In a cross-tabs analysis, for the children with presence of fidgety movements, the sensitivity of the quality of motor repertoire for predicting cognitive problems was 0.90 (95%CI: 0.60–0.98). The specificity was 0.58 (95% CI:0.39–0.76).
Grunewaldt et al. (2014)	NLBW group = *31 N*control group = 33 *M* GA (LBW group) = 26.1 (*SD* = 1.8) *M* birthweight (LBW group) = 773 g (*SD* = 146) No ranges are reported.	**Inclusion**: Birth weight < 1000 g **Exclusion**: Diagnosed congenital syndromes, follow up at a different hospital	**Motor:** Quality of motor repertoire (a specific aspect of GM). **Age:** 14 weeks post-term **Cognitive:** WISC III, Behavioral Rating Inventory of Executive Function (BRIEF) **Age:** 10 years	Prospective cohort study	Using General linear model, a normal motor repertoire at age 14 weeks predicted better scores on the working memory and processing speed scales of the WISC (mean difference = 19 respectively 23). No relations were found with total IQ and the verbal comprehension and perceptual organisation indices. No effect size or other statistics are reported.
Howe et al. (2016)	$N = 126$ Range GA 24–32 (*M* = 28.52, *SD* = 2.16) Range birth weight 572–1493 g (*M* = 1104.83, *SD* = 256.3)	**Inclusion**: age 5 (chronological), birthweight < 1500 g; GA < 32weeks, **Exclusion:** major cardiac, gastrointestinal, neurological, or congenital impairment, with neurological impairment including but not limited to documented abnormal neurological findings, cardiac impairment including but not limited to atrial and ventricular septal defects, gastrointestinal impairment including but not limited to necrotizing enterocolitis, and congenital impairment including but not limited to orofacial anomalies and Down's syndrome	**Motor:** Alberta Infant Motor Scales (AIMS) and motor scale of the BSID **Age:** 12 months **Cognitive:** WISC-III **Age:** 5 years	Retrospective cohort study	Hierarchical regression analysis showed that when controlling for background variables and for level of cognitive development at age 12 months (MDI) higher AIMS scores at 12 months predicted higher total WISC scores ($\beta = 0.24$, R^2total model = 0.39). The motor scale of the BSID at age 12 months did not predict IQ scores at age 5 years.
Kodric et al. (2010)	$N = 26$ Range GA 23–36 weeks (*M* = 30.19, *SD* = 3.87) Range birth weight 525g–3240 g (*M* = 1607.50, *SD* = 754.82)	Inclusion and exclusion criteria are not reported	**Motor:** Quality of GM **Age:** From term to 20 weeks post-term at 2–4-week intervals **Cognitive:** BSID II **Age:** Between age 2 and 3 years (*M* = 28.27 months, *SD* = 5.56 months)	Prospective convenience sample	Pearson correlation between optimality score at term age and MDI was 0.41 with medium effect size (Cohen's d – value not reported). Kruskal-Wallis one-way ANOVA by ranks showed significant differences in the MDI between groups with different qualities of GM at term age. Quality of GM at 3 months post term showed no relation with MDI scores.
Lefebvre et al.	$N = 160$	**Inclusion:** GA < 28.	**Motor:** Movement Assessment of Infants	Prospective cohort study	ANOVA shows that the high and low-risk

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Table 1 *(continued)*

Study (first author)	Participants	Exclusion/inclusion criteria of the study	Measures and age of measurement	Study design	Statistical test and effect size
(2016)	*M*GA = 26.3 (*SD* = 1.4) *M*birth weight = 906 (*SD* = 207) No ranges are reported	**Exclusion:** incomplete evaluation	(MAI, high risk cut-off set at 14) and Alberta Infant Motor Scales (AIMS, high risk cut-off set at 5th percentile) **Age:** 4 months **Cognitive:** BSID III **Age:** 18 months		groups for both the MAI and AIMS significantly differ on the cognitive and language scales of the BSID (Mean difference MAI cognitive = 6 language = 9, Mean difference AIMS cognitive = 5 language = 8). No further test statistics and effect sizes are reported.
Lundqvist-Persson et al. (2012)	*N* = 51 GA 24–36 (median = 34 weeks) No means and no information about birth weight are reported.	**Exclusion**: Congenital malformations and/or having mothers unfamiliar with the Swedish language Inclusion criteria are not reported	**Motor:** Quality of GM **Motor:** Term age and 3 months **Cognitive:** BSID **Age:** 3,6,10,18 months	Prospective convenience sample	Mann–Whitney *U* tests showed that children with lower quality of GM at term age had lower scores on MDI at 3, 6, 10 and 18 months. No relation was found between quality of GM at 3 months post term and MDI scores. No further test statistics and effect sizes are reported.
Montgomery et al. (2014)	*N* = 85 Range GA 22–32 (*M* = 28.5) Range birthweight 520–2030 (*M* = 1188) No standard deviations are reported	Inclusion and exclusion criteria are not reported	**Motor:** Level of motor development and quality of motor performance using a structured observation **Age:** 10 months **Cognitive:** BSID III **Age:** 2.5 years	Prospective	Pearson correlations showed that level of motor development (r = 0.34) and quality of motor performance (r = 0.26) at 10 months predicted BSID cognitive scale scores at 2.5 years. When controlling for gender and GA associations were only shown for level of motor development and only for boys (r = 0.39) and early preterm children (r = 0.53).
Spittle et al. (2013)	*N* = 99 *M* GA = 27.3 (*SD* = 1.5) *M* birthweight = 1008 g (*SD* = 265) No ranges are reported	**Inclusion**: GA < 30, living within 100 KM of the hospital, English speaking parents **Exclusion**: congenital abnormality known to affect development	**Motor:** Quality of GM **Age:** 1, 3 months **Cognitive:** BSID III Differential Ability Scale–Second Edition (DAS-II) **Age**: 2 years (BSID), 4 years (DAS)	Prospective cohort study. The sample is part of a larger randomised control study, for the current study data from both intervention and control groups were combined.	Multiple regression analysis showed that quality of GM at age 3 months predicted scores on cognitive and language scales at age 2 and 4 years. Mean differences were 7.4 (95%CI: 0.9,13.9) for BSID cognitive scale and 11.6 (95%CI: 3.1,20) for language scale, 14.3 (95%CI: 5.1, 23.9) for general conceptual ability (DAS-II), 11.6 (95%CI: 1.4, 21.8) for verbal reasoning (DAS-II) and 9.3 (95%CI: 3.6, 15) for nonverbal reasoning (DAS-II). No further test statistics or effect sizes are reported. Quality of GM at 1 month was not related to cognitive measures at 2 and 4 years.
Spittle et al. (2016)	*N* = 197 Range GA 32–36 (*M* = 34.4, *SD* = 1.2) *M* birth weight = 2161 g (*SD* = 463)	**Inclusion**: An English speaking parent **Exclusion**: congenital abnormality known to affect neurodevelopmental outcomes.	**Motor:** NNNS (including quality of movement scale), HNNE (including spontaneous movements scale) **Age:** At term age (38–44 weeks post-menstrual) **Cognitive:** BSID III **Age:** 2 years	Prospective cohort study	Logistic regression analysis controlling for age at time assessment, social risk and sex showed that suboptimal scores on the HNNE spontaneous movements scale predicted increased odds of cognitive delay on the BSID (Odds ratio = 3.13; 95% CI 1.29, 7.16). Scores of quality of movement on the NNNS were not related to cognitive scores. There was no relation found between the motor measures and the BSID language scale.
Van Baar et al. (2006)	N preterm = 34 Range GA 25–31(*M* = 28.6, *SD* = 1.7) Range birthweight 800–2090 g (*M* = 1291, *SD* = 319)	**Exclusion:** Multiplets, congenital malformations **Inclusion:** GA < 32	**Motor:** motor scale of the BSID **Age:** 6, 12, 18, 24 and 30 months **Cognitive:** BSID **Age:** 6, 12, 18, 24 and WISC	Prospective study.	Post hoc *t*-tests showed that children with school problems at age 10 years had lower WISC scores at this age (mean difference = 13, d = 1.02). These children also differed on their motor scores on the

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Table 1 *(continued)*

Study (first author)	Participants	Exclusion/inclusion criteria of the study	Measures and age of measurement	Study design	Statistical test and effect size
	N control group = 34 on term born children matched on background variables		**Age:** 10 years		BSID at age 12 months (mean difference = 16, d = 0.83). Cognitive scores at ages 6,2.18 and 24 months were not controlled for in the longitudinal analysis.
Wijnroks and van Veldhoven (2003)	N = 66 Range GA 25–36 (M = 32, SD = 3) Range birth weight 690–3210 g (M = 1668, SD = 631)	**Inclusion**: Relatively healthy infants No exclusion criteria are specifically reported	**Motor:** observation of postural control during exploration task at home. Infants were divided in three groups: no problems in postural control, extension of the elbows and clear signs of hyperextension. **Age:** 6 months **Cognitive:** BSID **Age:** 6, 12, 24 months Two own developed tasks measuring problem solving and attention **Age:** 18, 24 months	Prospective cohort study	Multivariate analysis of variance for repeated measures with postural control as a between subjects factor and the scores of the MDI of the BSID at 6, 12 and 24 months as a within subjects factor showed a main effect of postural control (F(2.58) = 7.60). Post hoc tests using the Bonferroni correction showed that signs of hyperextension predicted lower scores on MDI at all ages compared to the no problems in postural control group at all ages. Group differences in measures of problem solving were tested using ANCOVA with BSID motor scale as covariate controlling for the effect of motor development on problem solving. Significant group effects were found on both problem-solving tasks (F(2.60) = 4.41; F(2.57) = 10.40). Post-hoc tests showed that the signs of hyperextension group scored lower on the problem solving tasks than the no problems group. Group differences in inattention were analysed using Jonckheere Terpstra test with Mann Whitney U as post-hoc test, also controlling for motor development. Results revealed significant group differences at 24 months but not at 18 months. Post-hoc tests showed that children with elbow extension and signs of hyperextension were more inattentive than the adequate postural control group. No further statistics and effect size measures are reported.

Note. All ages are corrected ages. Not all measures included in the studies are reported in this table – only the measures relevant for this review are reported. Many of the studies also report the specificity and sensitivity of motor or GM assessment. We only report this where no other statistics are reported as the focus of this review is not on clinical diagnosis.

development we decided to include in this review also studies focussing on motor behaviour rather than on classical measures of motor development. These studies use assessment of the quality of the motor behaviour displayed by young children to predict their later cognitive development. First we review studies focussing on the quality of postural control and then we proceed to studies focussing on the quality of general movements.

3.2.1. Postural control

We found one study focussing on the relation between early postural control and later cognitive development in children born preterm. Wijnroks and van Veldhoven (2003) assessed postural control of infants born before 37 weeks of GA at age 6 months post-term and their performance on the cognitive scale of the BSID at ages 6, 18 and 24 months (post-term). Postural control was assessed as the infants were sat at a table exploring new objects. Normal postural control was seen when infants used both hands with flexed arms in front of the body to explore, and no signs of stretching or bouncing their back against the chair were observed. Results show that normal postural control predicted better performance on the cognitive tests at ages 6, 18 and 24 months (corrected age). The children with normal postural control also performed better on tests of problem solving skills and attention at ages 6 and 24 months, but not 18 months.

3.2.2. Quality of general movements

Many studies with children born preterm and with LWB focus on what is known as General Movements (GM). GM is a form of spontaneous movement of young infants. These movements involve the whole body and include arm, leg, neck, and trunk movements. The GM assessment developed by Prechtl is a method for observing these movements and evaluating movement aspects such as variability, complexity and frequency (Einspieler and Prechtl, 2005). Quality of GM is often seen as an indication for brain development (Zuk, 2011). Empirical work has shown that abnormal GM are related to various prenatal, perinatal and neonatal conditions and are specifically, though not exclusively, related to observable brain lesions (Hadders-Algra, 2004). Next to providing an indication of neurological integrity, GM's are a reflection of the infant's spontaneous motor behaviour or motor repertoire at the moment of measurement (Cioni and Prechtl, 1990). Therefore, while GM assessment clearly measures something different than instruments such as the AIMS or BSID and is usually used to test the integrity of the neurological system, it does provide an indication of spontaneous motor behaviour at an early age.

A recent review (Einspieler et al., 2016) shows that GM qualities at term age up to age one month post-term are consistently related to later cognitive skills. Effects were found on the cognitive scale of the BSID at age 2.5 years (Kodric et al., 2010), on scores of the DQ at age two years (Beccaria et al., 2012), lower scores on the MDI of the BSID at 3, 6, 10 and 18 months (Lundqvist-Persson et al., 2012) and at age 2 years (De Bock et al., 2017). Similarly, Bruggink et al., used weekly measures of GM and showed that children who had a normal GM or a GM becoming normal before 8 weeks performed better on cognitive tests (WISC) at age 7–11 years than children whose GM was abnormal at 8 weeks post-term. The children with abnormal GM in the first weeks of life (up to 8 weeks after term) also had poorer academic achievement (e.g., repeating a grade) (Bruggink et al., 2010). Thus, it seems that quality of GM up to age 8 weeks post-term is related to later cognitive outcomes. However, contrary to these findings, Spittle et al. (2013) report that in their study quality of GM at one month post-term was not predictive of children's scores on the mental scale of BSID at age 2 years (although this relation was marginally significant) and on the Differential Ability Scale (DAS) at age 4 years.

Evidence regarding quality of GM at 3 months post-term is more mixed. Several studies report no relation between GM at 3 months and DQ at age two years (Beccaria et al., 2012), MDI of the BSID at age 2.5 years (Kodric et al., 2010) and at ages 3, 6, 10 and 18 months (Lundqvist-Persson et al., 2012). Moreover, Bruggink and colleagues (2010) report that in their study no relation was found between GM becoming normal at 11 or 17 weeks after term and later cognitive outcomes. In contrast, Spittle et al. (2013) found that quality of GM at 3 months predicted scores on the MDI at age 2 years and on the DAS at age 4 years. In their review, Einspieler et al. (2016) suggest that evidence reveals that during the period of 3–5 months post-term specific aspects, rather than a general assessment of GM, are found to predict later cognitive outcomes. The number of normal postures (Butcher et al., 2009) and the smoothness of the movements (i.e., smooth and fluent vs. monotonous, jerky or stiff) (Fjørtoft et al., 2013) were found to predict IQ (as measured by the WISC) between ages 7 and 11 years. In contrast, another study has shown that lower scores on the smoothness of the movement at age 3 months post-term in children born with extremely LBW (below 1000 g) does not predict IQ at age 10 years. This aspect of GM did predict lower scores on executive functioning in general, working memory specifically, and attention at age 10 years (Grunewaldt et al., 2014). Thus, it seems that quality of GM in the first weeks post term (up to one months or up to 8 weeks) is related to later cognitive development, whereas from 3 months post term only specific qualities of GM are related to later cognitive development. However, the evidence is still mixed.

Findings from two additional studies using different instruments that measure constructs that are similar to the GM assessment paint a picture similar to the results of the GM studies. Spittle et al. (2016) showed that spontaneous movements assessed by the Hammersmith Neonatal Neurological Examination (Dubowitz et al., 1988) at term age are predictive of BSID cognitive scores at age 2 years. In this study, however, quality of movement as measured by the NICU Network Neurobehavioral Scale (Lester et al., 2004) was not predictive of BSID cognitive scores. A recent population study showed that quantity and quality of mobility as measured at the NICU were predictive of WISC scores at age 26 years (Breeman et al., 2017).

Thus, the evidence suggests that poor quality of GM early in life is related to poorer cognitive skills later in life. Some confusion exists regarding the timing of measurement of GM. Most studies find effects of GM at term age and one month post-term, while others suggest that also GM at 3 months post-term is an important predictor. These differences might be related to differences in characteristics of the children participating in the different studies (such as GA and birth weight). Additionally, specific aspects of GM assessment, such as evaluation of postures, level of activity, frequency of movements and the smoothness of the movements predict cognitive skills later in life (at least up to age 11 years). Most studies agree that these aspects should be measured at age 3–5 months post-term.

4. Discussion

The current paper aimed to review the existing evidence linking early motor development and motor behaviour of children born preterm and/or with LBW with later cognitive outcomes. It is clear that the empirical evidence pertaining to these children is still scarce and most studies still need to be replicated (see also Einspieler et al., 2016). We found 5 studies addressing the link between motor development and later cognitive outcomes and additional 12 studies addressing the link between early postural control and quality of GM and later cognitive development (see Table 1). These studies show a relatively consistent link between level of early motor development and later cognitive skills and between quality of postural control and GM and later cognitive skills. However, given the small number of studies and several limitations this conclusion can only be drawn with caution.

Only a small number of studies reports evidence linking level of motor development with later cognitive development in children born preterm and/or with LBW. The results are not always consistent, though they usually do suggest a link exists. However, and more importantly, all studies, but one, do not control for early cognitive development. As these children display cognitive and motor impairments early in life, it is possible that cross-sectional relations between motor and cognitive development early in life explain the longitudinal relations between motor and cognitive development. It is important for future studies to take this aspect into account in their analysis to enable more definite conclusions.

The findings presented in this review are in line with studies done with different populations. The evidence regarding postural control are further supported by data from two recent studies showing a link between sitting skills and attentional – cognitive skills in both children with motor delay and children with Cerebral Palsy (Harbourne et al., 2014; Surkar et al., 2015). Moreover, the link between level of motor development and cognitive skills is also found in typically developing term-born children (e.g., Oudgenoeg-Paz et al., 2015). However, unlike evidence found in term born, typically developing children, most evidence in children born preterm or with LBW relates to the quality of movement or postural control rather than to timing of (gross) motor development. In addition, the evidence from these studies concerns mainly measures taken from general tests of both motor and cognitive skills. Evidence from term born, typically developing children provides more specific links between specific motor skills and specific cognitive skills (e.g., Frick and Möhring, 2013; Soska et al., 2010).

The evidence from term born children showing specific links is in line with the embodied cognition approach rather than general cognitive impairment. Theoretically also in children born preterm and/or with LBW if motor skills are of poor quality, the benefits to cognition from sensorimotor interactions with the physical world are expected to be lower. Poor quality movements provide children with different information about their movements and about the environment, and this information is less optimally supportive of their cognitive development (see also Hadders-Algra, 2000). However, the evidence from children born preterm or with LBW is still not sufficient to draw firm conclusions regarding this issue. More research is needed, investigating such specific links in these children. For example, Wijnroks and van Veldhoven (2003) show a link between postural control (sitting) and later cognitive skills in children born preterm. In the literature concerning typically developing children, a link between sitting skill and the specific cognitive skills of 3D perception and mental rotation is reported (Möhring and Frick, 2013; Soska et al., 2010). These links are (at least partially) explained by the object exploration made possible by the acquisition of the skill of sitting. A different study with children born preterm reports that children born preterm had less well developed object exploration skills, compared to children born at term (Lobo et al., 2015). Taken together, these studies might suggest that also in children born preterm, such a link might occur between sitting, object exploration and specific cognitive skills, such as 3D perception and mental rotation. However, this relation has not been directly tested, therefore, this remains an hypothesis. Moreover, given the widespread motor and cognitive impairment seen in children born preterm and/or with LBW, such a link might also be the result of general brain impairment.

As previously noted, children born preterm and/or with LBW show widespread brain injury that affects both motor and cognitive regions in the brain and results in both motor and cognitive deficits. Multiple studies provide evidence for such disruption to global brain development (de Kieviet et al., 2014; de Vries et al., 2015; Volpe, 2009). Thus, the longitudinal links between motor and cognitive skills might be the results of such brain injury. Similarly, lower quality GM early in life may be an indication of such general impairment reflected in disrupted brain development that hampers cognitive development independently of motor impairments. Testing hypotheses regarding specific or general links between motor and cognitive development will enable researchers to provide support for one of the two theories. This work will need to be longitudinal and include measurements of both early motor skills and specific cognitive skills as well as measurements of possible underlying mechanisms such as exploration behaviour or brain damage. It is especially important to test links which are not expected from an embodied view but are expected from a general impairment perspective. For example, from an embodied cognition view a link between sitting and 3D perception is expected (see Soska et al., 2010) but a link between other gross motor milestones, such as rolling from prone to supine position, and 3D perception would not be expected.

Moreover, another possibility is that in children born preterm or with LBW evidence will be found for both a general impairment that influences both early motor and cognitive skills and for specific developmental cascades that link such early motor impairments with later cognitive outcomes. Thus, the two theoretical accounts are not necessarily mutually exclusive. It is possible that later cognitive development will be found to only partially be dependent on motor development and could also partially be explained by general impairment.

The link between motor and cognitive development has implications for early diagnosis and intervention. At the moment, most early interventions offered to children born preterm or with LBW have not been successful at advancing their cognitive skills in the long term (Lobo et al., 2013; Spittle et al., 2015; Van der Veen et al., 2009). Interventions based on motor behaviour as a tool to advance development across domains may prove to be the key to this problem. Such interventions could target a set of motor behaviours early in life, which are thought to be fundamental in development and will therefore focus on minimizing cognitive delays before these even occur (Lobo et al., 2013; Spittle et al., 2015; Van der Veen et al., 2009). One promising early intervention programme that does appear to be effective is the Infant Behavioural Assessment and Intervention Programme (Hedlund, 1998). This programme aims to support multiple developmental functions of children born preterm through responsive parent-child interactions. The programme includes a number of therapy sessions with a physical therapist in the children's home up to age six months post-term. Parents receive advice on how to best support their child's skills in exploring the world and processing sensory information. Next to the socio-emotional component, this programme has a strong motor component as parents are taught for example about positioning and handling of the infant (e.g., positioning in prone position) (Hedlund, 1998). The first evaluations of this programme indicate that besides doing better on motor development, children who followed this programme also showed better performance IQ and self-regulation skills at age 5.5 years when compared to children who followed the standard care (Van Hus et al., 2013; Verkerk et al., 2011). Thus, targeting early motor development seems to have effects going beyond just the motor domain and lasting until at least age 5.5 years. More research is needed in order to replicate these effects and determine their duration.

4.1. Limitations

The number of studies included in this review is relatively small, making it difficult to draw firm conclusions. Moreover, as most studies did not control for possible confounding factors such as early cognitive development, the conclusions should be drawn with caution.

A number of key characteristics of the populations included in the different studies varied between studies. For example, most studies excluded children with known neurological impairments (e.g., Spittle et al., 2016; Wijnroks and van Veldhoven, 2003), but not all studies did so (e.g., Breeman et al., 2017; Lefebvre et al., 2016). In addition the range of gestational age and birth weight varied between the studies as well. That is, some studies included children below 34 or 32 weeks of gestational age, while other included children from the full range of gestational ages considered preterm (i.e., below 37 weeks). In the future, when more studies addressing this issue will be published, studies could be grouped according to more specific definitions of the population, thus enabling more precise conclusions. Finally, all relevant studies were included without selecting studies based on their design or quality. However, given the small number of studies available, this might be seen as an advantage as it enabled us to present all relevant information in a more comprehensive manner. Exclusion of studies based on design and quality might significantly reduce the amount of evidence reviewed and that is not desirable in a field where empirical evidence is still scarce. In time, when more empirical studies in this field addressing this longitudinal link will be published, a comprehensive systematic review, applying rigorous quality control could be performed, based on which more definite conclusions can be drawn.

4.2. Future directions

Given the limited amount of evidence in this field, more research is clearly needed. Future studies should pay attention to individual developmental trajectories of children born preterm or with LBW focusing on development in multiple domains. Such studies would shed more light on the specific links between developmental domains and between early and later development. Another realm for future work is in the area of mechanisms underlying links between motor and cognitive development. Possible factors suggested as mediators of this link in term born, typically developing children include exploration behaviour (Oudgenoeg-Paz et al., 2015; Walle and Campos, 2014), selective attention (Campos et al., 2000) and social interaction (Clearfield, 2011; Karasik et al., 2012). Motor development has been shown to be related to advances in these areas and these advances, in turn, have been related to cognitive advances in domains such as spatial cognition and language. However, in children born preterm and/or with LBW, the studies should also include measures of brain development and neurological functioning, as the links can also be explained by general a widespread brain injury. Moreover, and in line with this general impairment idea, it is important that future studies control for early level of cognitive development as a possible confounding factor.

Next to looking for possible mediators and confounding factors, researchers should also look for factors moderating these links. Some conditions might prevent children from benefiting from their interactions with the world while others will increase their benefits. Such conditions might include suffering from intrauterine growth restriction, being moderately preterm or very preterm, birth weight and characteristics of the physical and social environment in which children grow. These factors might influence the stimulation children receive from their environment and/or the extent to which they can profit from this stimulation and thus the specific links between motor and cognitive skills. These situations might of course also influence the neurological development of these children and thus their subsequent motor and cognitive development.

Obtaining such evidence about individual trajectories, developmental mechanisms and the factors influencing them is important for early diagnosis of children at risk for developing cognitive impairments and for the development of 'tailor made' interventions. Such intervention programmes will be able to focus on the developmental mechanisms that might be impaired due to early motor impairment and adjusted to the specific situation of individual children, thus increasing the chances of success in preventing future cognitive impairments. Even if the link between early motor development and later cognitive skills is due to a general (brain) impairment, better motor functioning might still contribute to improvement of later cognitive functioning (see for example Van Hus et al., 2013; Verkerk et al., 2011).

4.3. Conclusion

This review focused on the link between early motor development and later cognitive outcomes in children born preterm or with LBW. The existing evidence to date shows mainly that the quality of general movement and postural control early in life is predictive of later cognitive outcomes. These findings are in line with both an embodied cognition approach and the general impairment hypothesis. In recent years a growing body of evidence from typically developing children suggests that early motor development is important for many aspects of later cognitive development. This field of research needs to be explored further regarding children born preterm and/or with LBW. This is especially important given the potential such links hold for developing effective early interventions for these children. More work is needed in order to determine if the relations found between early motor skills and later cognitive outcomes are specific or general, and to entangle the factors mediating and moderating this link.

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