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The impact of motor development on typical and atypical social cognition and language: A systematic review

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Abstract

Background: Motor development allows infants to gain knowledge of the world but its vital role in social development is often ignored. **Method:** A systematic search for papers investigating the relationship between motor and social skills was conducted, including research in typical development and in Developmental Coordination Disorder, Autism Spectrum Disorders and Specific Language Impairment. **Results:** The search identified 42 studies, many of which highlighted a significant relationship between motor skills and the development of social cognition, language and social interactions. **Conclusions:** This complex relationship requires more attention from researchers and practitioners, allowing the development of more tailored intervention techniques for those at risk of motor, social and language difficulties.

Key Practitioner Message

- Significant relationships exist between the development of motor skills, social cognition, language and social interactions in typical and atypical development
- Practitioners should be aware of the relationships between these aspects of development and understand the impact that early motor difficulties may have on later social skills
- Complex relationships between motor and social skills are evident in children with ASD, DCD and SLI
- Early screening and more targeted interventions may be appropriate

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The achievement of motor milestones is recognised by parents as an important landmark in their infant's development, but the significance of these milestones for the development of other key skills has not always been appreciated. Developing motor skills allows the infant to act on, and interact with, the environment in increasingly complex ways and it is this interaction that informs the infant's knowledge of the world (Piaget 1953, von Hofsten 2004). At the earliest stages, motor development is constrained by the infant's brain and body growth, with external influences, such as parental encouragement and the type of home environment, increasing in influence as infants improve their control over their own bodies (Berk, 2006). The interaction of these different constraints on a number of subsystems results in the nonlinear development of particular behaviours, such as learning to walk, and contributes to the wide variation in motor skills in infants and children. Using this 'dynamic systems' framework (Thelen & Smith, 1994), it is possible to see how a relatively small disruption in one of the interacting systems could be compounded and have escalating effects on other systems involved in motor development. It can also explain how seemingly unrelated domains, such as motor and social cognitive development (i.e., language, face processing), become increasingly intertwined with age.

In infants and children who develop atypically, a neurological disruption in one specific area could reflect a common cause for a variety of developmental difficulties, even if the core symptoms on which different neurodevelopmental disorders are diagnosed are seemingly disparate (e.g., Gilger & Kaplan, 2001: 'Atypical Brain Development' framework). Thus, researchers are increasingly recognising the effect that motor skills have on other areas of development, such as social and cognitive abilities, and are highlighting this relationship in both typically-developing infants and children, and in those who are diagnosed with a neurodevelopmental disorder. The current review will consider the relationship between motor and social cognitive abilities in typical development, and will then focus specifically on three neurodevelopmental disorders, namely Developmental Coordination Disorder (DCD), Specific Language Impairment (SLI) and Autism Spectrum Disorders (ASD).

Motor dysfunction in neurodevelopmental disorders

Motor dysfunction is central to the diagnosis of DCD (previously 'clumsy child syndrome', and also sometimes referred to as 'dyspraxia'), which affects between 2-5% of the population (Lingam et al., 2009; American Psychiatric Association, 2000, respectively) and is usually diagnosed between the ages of 6-12 years (Barnhart et al., 2003). Motor impairment in DCD must not be due to any general medical condition (e.g., cerebral palsy) and must exceed any impairment that would be expected from developmental delay (DSM-IV TR: APA, 2000). While motor difficulties are key to the disorder, research also highlights problems in social interaction and play (Kennedy-Behr, Rodger & Mickan, 2011), language (Archibald & Alloway, 2008) and processing emotional faces (Cummins, Piek, & Dyck, 2005), which are difficulties more usually associated with other neurodevelopmental disorders, such as SLI or ASD.

Motor atypicalities have been highlighted in SLI, suggesting that the language difficulties in this disorder may not be as 'specific' as implied by the diagnostic label (Hill, 2001; Ullman & Pierpont, 2005). SLI affects around 7% of the population (Tomblin et al., 1997), and motor difficulties have been reported in between 40-90% of these children (Hill, 2001), with the most common figure being around 70% (e.g.,

Hill, 1998). These motor atypicalities appear wide ranging, affecting fine and gross motor skill as well as praxis ability (see Hill, 2001, for a review). An increasing number of studies have also highlighted motor difficulties and atypicalities in individuals with ASD, which affects around 1% of the population (Baird et al., 2006). Although repetitive and stereotyped behaviours are part of the triad of impairments used for diagnosing ASD, motor dysfunction, including gross and fine motor impairments and difficulties in motor planning, are not central to the diagnostic criteria despite being reported in these individuals. Again, research has identified poor or atypical motor functioning across a wide range of tasks in adults, children and infants at familial risk of developing ASD (see Bhat, Landa, & Galloway, 2011, for a review). While it is important to highlight motor dysfunction as a factor in these neurodevelopmental disorders, it is now crucial that we consider the *relationships* between poor motor skill and the social cognitive difficulties that are found in SLI and ASD, as well as elucidating these links in DCD. The current paper therefore aims to review the evidence for links between motor and social cognitive skills in typical and atypical development, making suggestions for future research and for clinical and educational practice.

Methodology

A systematic search of two electronic databases (PsychINFO and PubMed) was conducted between 17th December 2012 - 7th January 2013. To provide the opportunity to locate as many studies as possible, broad search terms were used, including 'motor' or 'movement' in combination with 'social' or 'language', and these were identified by the search engine from either the title and/or abstract. In all, more than 13,000 papers were identified on these databases using these search terms, of which the majority were not relevant to the purpose of this task, being unrelated to motor, social or language skills. The search was then narrowed to meet the following inclusion criteria: the paper must (1) be a peer-reviewed article, (2) be published between the years 1993 and 2013, (3) be written in English, (4) present data for at least one group of participants between the ages of 1 month and 18 years, (5) include participants without a known medical condition, e.g., cerebral palsy / stroke / traumatic brain injury, or low birth weight / very premature birth, (6) include quantitative assessment of the relationships between motor *and* social-cognitive abilities (e.g., language / face processing) or motor skill *and* social well-being (e.g., participation / friendships / prosocial vs antisocial behavior). Motor skill was defined here as relating to the development of gross and/or fine motor abilities, or the achievement of relevant gross and/or fine motor milestones. The development of gestural use, imitation and oral-motor skills fall outside of this definition and are included in other published reviews.

In the first stage of the literature search, titles and abstracts of identified articles were assessed in terms of these inclusion criteria, along with additional articles known to the authors. In addition, any duplicates produced by the two search engines were removed. This produced a total of 90 relevant articles. In the second stage, the full text of each article was retrieved and considered for inclusion, resulting in 36 being retained for the review. In the final stage, the reference lists of these full-text articles were searched and any relevant papers fitting the inclusion criteria were added. At the end of this process, 43 papers were included in the review.

Results

Overview of studies

Of the 43 studies included in this review, 18 were concerned with typically-

developing infants and children, and 17 of these studies investigated development in infancy and the early years (Table 1). The remaining 25 studies concerned atypical development, of which 13 were related to ASD, 7 to DCD and 5 to SLI (Table 2). Presumably due to the relatively late diagnosis of these neurodevelopmental disorders, the majority of these studies ($N=15$) investigated development in the school years. Studies investigating infant development ($N=5$) were all related to ASD, using either prospective designs with infants at-risk of developing ASD (due to having an older sibling diagnosed with the disorder), or by using retrospective parental reports about children diagnosed with ASD as toddlers.

--- Table 1 about here ---

Relationships between motor and social functioning in typically-developing infants

During infancy, several investigations observed naturally-occurring motor and social behaviours or language precursors. Five of these studies (Ejiri, 1998; Ejiri & Masataka, 2001; Eilers et al., 1993; Iverson et al., 2007; Locke et al., 1995) found that rhythmical arm movements increased in the time leading up to the onset of ‘canonical’ babbling (a type of rhythmical babbling that consists of repeated consonant-vowel syllables, such as “babababa”), and decreased again after this time. Iverson (2010) suggests that this pattern is important because the two rhythmical activities share many properties, and the motor movements provide opportunities for infants to practice the skills required for canonical babbling and to receive multimodal feedback as a consequence of their actions. Four other studies reported a significant relationship between naturally-occurring gross motor development and social behaviour, including social gaze and bids for social interaction. However, while Fogel et al., (1999) found that more developed motor skills (i.e., maintaining an upright posture) related to reduced gaze to the mother’s face, others found that development from crawling to walking produced more advanced social interaction behaviours in infants (Clearfield, Osborne & Mullen, 2008; Karasik, Tamis-LeMonda & Adolph, 2011). It seems likely that younger infants who are placed in upright postures are eager to visually explore their environment, resulting in fewer looks to the parent. On the other hand, infants going through the transition from crawling to walking are provided with many more opportunities to actively explore the environment and seek to share these experiences with others, resulting in more social bids. Indeed, Clearfield (2011) reported that infants interacted more with their mothers and produced more directed gestures as independent walkers compared to crawlers, supporting the theory that the development of locomotion changes a child’s exploration of the environment and interaction with those around them (e.g., Campos et al., 2000).

The final three studies of infant development used standardised tests and questionnaires relating to motor and language development (Alcock & Krawczyk, 2010) and experimental measures of motor skill and social behaviour (Libertus & Needham, 2010, 2011). Alcock and Krawczyk (2010) reported concurrent relationships between gross and fine motor abilities and language development, assessed through parent questionnaires, but no relationship between these language skills and gross and fine motor skills measured by the Bayley Scales of Intellectual Development (BSID-II; Bayley, 1993). Differences between parent-reported and experimenter-observed motor skills are important, as studies with older children and those with neurodevelopmental disorders often use both or rely on retrospective parent reports of motor abilities in their samples. The significant relationship

identified between parent reports of motor and language skills in the study by Alcock and Krawczyk (2010) could depend on both being measured through questionnaire, while the non-significant relationship was found when motor ability was measured through a different technique. However, it could also relate to the sensitivity of different instruments: it is more difficult to see an infant's range of motor skills in the standardised testing environment than on a day-to-day basis.

These problems are avoided by the use of experimental manipulations of motor abilities in the two studies by Libertus and Needham (2010, 2011), which also allowed the effects of age and motor skill to be disentangled. The studies promoted manual manipulation and exploration of objects in three-month-old infants (an earlier age than they would usually be able to reach and grasp objects) by training them to use 'sticky mittens'. Other infants of the same age either passively interacted with objects or received no training at all. As in Fogel et al. (1999), the new opportunities for visual exploration resulted in fewer looks by the infants to the person interacting with them, suggesting that the new object was much more interesting to the infants (Libertus & Needham, 2010). However, when presented with simultaneous images of toys and faces in an eyetracking paradigm, infants receiving active training with the sticky mittens were more likely to orient to the face and to spend longer looking at the face than the object (Libertus & Needham, 2011), a pattern that mirrored older untrained infants, but not the three-month-olds in the passive- or no-training conditions. It is possible that this may be due to the trained infants becoming habituated or 'bored' with the object, and therefore showing a preference for the face when both were presented. On the other hand, the fact that these infants showed the same pattern as untrained older infants might suggest that the intense training is increasing their rate of maturation. However, it is difficult to untangle these alternative conclusions within the eyetracking study. These studies therefore demonstrate differences between social gaze during interactions with people and objects, and in social cognition tasks presented in the laboratory. It is important to bear this in mind when considering the results of other studies, particularly with older children, which rely on the latter tasks to understand social cognition.

Relationships between motor and social functioning in typically-developing children

Of the six remaining studies of typical development, five used standardised measures of motor abilities while one relied on parent reports of motor and communication abilities. The latter questionnaire-based study by Wang et al., (2012) analysed data collected as part of a large-scale cohort study, using data from parent reports at 18 months and at 3 years from 62,944 participants. Having such a large dataset is extremely useful in attempting to assess the complex relationships between motor and communication skills, and these analyses suggested that motor and communication skills at 18 months were equally good predictors of communication skill at 3 years. Interestingly, the analyses also revealed that early motor skills were a better predictor of later communication skills than early communication skills were of later motor skills, supporting the theory that early variance in motor abilities is useful in understanding later development of language and communication.

Two other studies of older children used longitudinal designs and reported relationships between motor function at 5-6 years and a range of social behaviours at 6-7 years (Bart, Hajami, & Bar-Haim, 2007), and between motor abilities at 6-7 years and social status with peers at 9-10 years (Ommundsen, Gunderson, & Mjaavatn, (2010). Specifically, Bart et al. (2007) found that earlier motor function, as assessed by an Occupational Therapist, could predict later teacher reports of scholastic

adaptation, disruptive, anxious-withdrawn and prosocial behaviours, although the strongest relationships were with scholastic adaptation and disruptive behaviours. It is possible that this could explain differences in social status found in children with poorer motor skills by Ommundsen et al. (2010). It could also relate to the reduction in social play and increased social reticence reported in children with poor motor skills (Bar-Haim & Bart, 2006). In the final two studies in Table 1, poor motor skills were related to poor performance on a standardised test of language development (Cheng et al., 2009), and on experimental tests of emotion comprehension (Piek et al., 2008), which could be contributing factors to a child's ability to play and interact with other children in a socially-acceptable way, and could therefore influence the child's later social standing with peers. Given the relationship between earlier peer acceptance or friendships and later academic achievement (e.g., Wentzel & Caldwell, 1997) and adult adjustment (e.g., Bagwell, Newcomb, & Bukowski, 1998), understanding the possible risks associated with poor motor skills on the development of appropriate social behaviour and friendships could have far-reaching consequences.

--- Table 2 about here ---

Relationships between motor and social functioning in atypical development

Moving on to atypical development, this section will now consider each of the neurodevelopmental disorders in turn, beginning with infant studies in ASD. Using retrospective reports of manual motor skills in children with an ASD diagnosis, Gernsbacher et al. (2008) found that children classified as having highly fluent speech in an assessment by a speech-language professional were reported to have much better manual motor skills in early life than those with moderately fluent or minimally fluent speech. Reports of the early manual motor skills of a proportion of the children were corroborated by home video analysis by researchers blind to the results of the caregiver interview. On the other hand, Kim (2008) reported no significant correlations between retrospective reports of motor and language milestones and current parent reports of language and motor functioning. The study by Gernsbacher et al. (2008) used a landmark-based interview, which may have helped to improve recollection of the early motor milestones and make the results more reliable (as supported by the corroboration of the parent report by home video analysis), and this might explain the differences between results. However, the period of time between these milestones and the report was very long in some cases (up to around 17 years), and only a small proportion of the original sample also provided home videos for analysis. Retrospective reports from the other parents involved in the study could have been biased by knowledge of the child's later development. For this reason, *prospective* studies of infants at-risk of developing ASD are likely to provide more reliable results concerning the relationship between motor and social skills during infancy. Although the 'infant siblings' design is being used increasingly to help understand the characteristics leading to an ASD diagnosis (see Elsabbagh & Johnson, 2009, for a review), only three papers specifically address the relationship between motor and social development in these infants. Iverson and Wozniak (2007) investigated the relationship between canonical babbling and rhythmic arm movements in at-risk infants, and reported a similar pattern to that in typically-developing (TD) infants: rhythmical arm movements increased until the onset of canonical babbling, after which they decreased. However, the change in rate of rhythmical arm movements between sessions was much lower for the at-risk infants

than for the low-risk infants. These early differences in motor behaviour were also found to be important in the development of later communication and face processing abilities, with poorer motor skills associated with communication delay at 18 months (Bhat, Galloway, & Landa, 2012), and with difficulties in processing gaze direction and emotional facial expressions at 5-7 years (Leonard et al., in press). More studies investigating these relationships with larger samples will be important in our future understanding of infant development in ASD.

A further eight studies have investigated the relationship between motor and social development in older children and adolescents with a diagnosis of ASD. Four of these studies reported significant correlations between motor skill and socialisation (Sipes, Matson, & Horovitz, 2011) and degree of social impairment (Dyck et al., 2007; Hilton et al., 2007; Hilton et al., 2011; Perry et al., 2009). In addition, a study conducted by Dyck et al., (2006) reported significant correlations between motor coordination and experimental measures of emotion recognition, emotion understanding and theory of mind scores, with these correlations significantly stronger in the ASD group than in the TD group. While Hsu et al., (2004) also reported significant correlations between motor skill and expressive language, social comprehension and personal social development, gross and fine motor abilities were not significant predictors of personal social development over and above social comprehension scores. Finally, Dziuk et al. (2007) found that basic motor skill did not predict social impairment scores on the Autism Diagnostic Observation Schedule (ADOS: Lord et al., 1999), although the ability to perform gestures was significantly associated with ADOS scores. It is interesting to note that those studies in which significant correlations are found between degree of social impairment and motor skills use parent report measures of autistic tendencies, such as the Social Responsiveness Scale (SRS: Constantino & Gruber, 2005, used by Hilton et al., 2007, 2011), the Social Communication Questionnaire (SCQ: Rutter, Bailey, & Lord, 2003) and the Autism Diagnostic Interview (ADI: Lord, Rutter, & Le Couteur, 1994), both used by Dyck et al. (2007). Future studies combining parent report, experimental and standardised measures of motor and social functioning will be vital in understanding the relationships between these abilities in ASD.

There has been increasing interest in the social functioning and behaviour of children with DCD, but relatively few studies have considered the relationship between the level of motor skills and these social outcomes. Of the seven studies that have assessed this relationship, only four of them included children with a full clinical diagnosis of DCD (Green, Baird, & Sugden, 2006; Jarus et al., 2011; Poulsen, Johnson, & Ziviani, 2011; Wagner et al., 2012), while the other three studies used a standardised measure of motor ability to identify children 'at-risk' of DCD in typically-developing populations, i.e., children with severe or moderate movement difficulties based on these motor measures (Cummins et al., 2005; Kanioglou, Tsorbatzoudis, & Barkoukis, 2005; Schoemaker & Kalvaboer, 1994). This screening procedure is useful because it can identify children with movement difficulties that have not been identified by teachers or parents, which may be due to lack of awareness about DCD, or may be because these children do not have other obvious co-occurring difficulties in language, attention or other domains, which may be more likely to result in referral to clinical services.

Both clinical and screening studies have reported significant correlations between motor abilities and parent-reported peer or social problems (Cummins et al., 2005; Green et al., 2006; Wagner et al., 2012), and Jarus (2011) found that children with poorer motor skills conducted more social activities alone (across TD and DCD

groups). While there were significant correlations between motor abilities and parent-reported “socially-negative behaviour” in both TD and DCD groups, Schoemaker and Kalvaboer (1994), reported that the children with the poorest motor skills were actually less likely to show these behaviours than those with only moderate motor difficulties. Kanioglou et al. (2005) also reported that children with moderate motor difficulties were more likely to face social rejection than their TD peers, although differences between the TD group and the children with the most severe movement difficulties were not significant. It is difficult to unpick this unexpected pattern of results, as information such as the intellectual level of the children with motor difficulties is not provided, and this and other factors are likely to interact with the way that peers interact with children with movement difficulties. However, from the information that was collected, it appears that those children with the most severe movement difficulties also had more attention and conduct problems than their TD peers (Kanioglou et al., 2005). It is possible that other children were more accommodating to those with severe movement difficulties, as these other behaviours were more likely to be identified as ‘atypical’, and, therefore, to be taken into account during interactions. This may also be related to the reports of fewer socially-negative behaviours in those with the most severe movement difficulties, with children with more obvious difficulties perhaps less likely to try to hide their movement problems with aggressive or foolish behaviour (Schoemaker & Kalvaboer, 1994). In addition, the research by Poulsen et al. (2011) suggests that peer relations and social activities might be affected by the *type* of movement difficulty displayed by the child. For example, boys with DCD who had relatively poorer manual dexterity and ball skills (compared to balance) were less likely to participate in informal physical activities with peers. Different profiles of motor functioning, and the number and type of co-occurring difficulties (such as attention problems, e.g., Martin, Piek, & Hay, 2006), could therefore affect both the diagnosis and outcomes of children with DCD, and these interacting factors should be considered carefully in future research.

While research into children with ASD and DCD tends to focus on the relationship between motor skills and social behaviour or impairments, the motivation in studies of SLI is, understandably, to assess the role of motor abilities in the atypical development of language in this neurodevelopmental disorder. In children with SLI, locomotion or gross motor scores were significantly correlated with auditory comprehension and verbal ability (Merriman & Barnett, 1995), and with communication scores (Webster et al., 2005) and articulation (Vukovic, Vukovic, & Stojanovic, 2010). Parent-reported gross motor skill during early childhood significantly predicted ‘successful’ expressive language (i.e., scores above the 10th percentile) in children with a diagnosis of SLI at 7 years (Paul & Fountain, 1999). Fine motor scores were significantly correlated with an expressive language composite (Iverson & Braddock, 2006), articulation (Vukovic et al., 2010) and communication (Webster et al., 2005), but not with auditory comprehension and verbal ability (Merriman & Barnett, 1995). This relationship between language development and gross motor skill in SLI can be linked back to the studies of typically-developing infants, which suggested that changes in locomotion around the environment resulted in infants interacting in different ways with their parents, including more social bids and directed gestures (Clearfield, 2011; Clearfield et al., 2008; Karasik et al., 2011). It seems that reduced or delayed locomotion could therefore be a contributing factor in the development of language difficulties in children with SLI, although more longitudinal studies assessing the relative contributions of different skills to language development in SLI are needed before this

speculation can be supported.

Discussion

The current paper has considered the relationships between developing motor and social skills in both typical and atypical cases and has highlighted the range of motor and social difficulties found in three neurodevelopmental disorders (ASD, DCD and SLI). It is evident from these studies that developing motor skill can influence the number and types of opportunities that infants and children have to interact with others, and the consequent development of social relationships. Poor or atypical motor development could therefore be an important contributing factor to problems with language, social communication and understanding and social interaction that are found in several neurodevelopmental disorders. This review also highlights the differences found across parental report, standardised and experimental measures of motor and social development, as well as differences in the focus of investigations in typical and atypical development. Ideally, future research will be able to combine these methods to assess development across groups, allowing more cross-talk between researchers of typical and atypical development, and producing clearer answers concerning the role of motor skills in the development of other domains.

So what are the implications for both academic and clinical practice? First, it is clear that we need to communicate the fact that motor development is not an independent process, but has rich and complex relationships with the development of other cognitive domains. The ‘dynamic systems’ approach (Thelen & Smith, 1994) is an excellent demonstration of this notion, and can explain how seemingly independent skills, such as motor control and language, can be linked through similar underlying processes within the same system (Iverson, 2010). It also specifies constraints on the developing system, including environmental and social factors that affect how and when different skills develop. These constraints may also be underlying neurological deficits, which may play a more significant role in atypical development (Gilger & Kaplan, 2001). These neurological deficits may also contribute to the high rate of co-occurring symptoms across the neurodevelopmental disorders reviewed in this paper (e.g., Gillberg, 2010). Second, we need to think *developmentally* when researching neurodevelopmental disorders, which will aid the understanding of how early motor differences could have cascading effects on a range of different developmental skills (Bishop, 1997; Karmiloff-Smith, 1998, 2009). It is important to remember that these alternative developmental pathways may also result in compensatory strategies in other cognitive domains, and these relative strengths and weaknesses are just as important to investigate as any deficits. Third, more research needs to be conducted into the developing relationships between motor and social functioning in infancy in neurodevelopmental disorders. Although this presents challenges, as many neurodevelopmental disorders are not diagnosed until at least preschool, and often not until the school years, we need to begin to face these challenges and consider ways to overcome them. Some neurodevelopmental disorders, such as Down syndrome and Williams syndrome, have well-known genetic bases and can be diagnosed relatively early, allowing similar studies to be carried out across these groups as in typically-developing infants. For those neurodevelopmental disorders with a relatively late diagnosis, one method is to use prospective studies, such as those conducted with infants at increased risk of developing ASD, to follow motor and cognitive development over infancy in those that do and do not go on to develop the disorder. Screening projects, in which infants performing below average

in motor development can be identified and followed longitudinally, can also be carried out to help understand the complex, changing relationships between motor abilities and other domains and to assess which children go on to develop difficulties associated with particular neurodevelopmental disorders. Understanding the different profiles of motor, social and cognitive skills will allow more targeted interventions for distinct patterns of development, and could have important implications for the quality of life, psychological and physical health of individuals with neurodevelopmental disorders.

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Table 1. Studies investigating the relationship between motor and social abilities in typically-developing infants and children

Reference	Age of participants	Motor behaviour task	Social behaviour / language task	Results
<i>Infancy</i>				
Fogel <i>et al.</i> (1999)	1-6 months (within-subjects)	Infant's naturally-occurring postures during observation session	Infant's naturally-occurring gaze during observation session	<ul style="list-style-type: none"> • Infants were significantly more likely to gaze away from the mother's face when in an upright position, compared to a non-upright position, regardless of age. • Posture accounted for unique variance in gaze toward the mother, over and above the age of the infant
Iverson <i>et al.</i> (2007)	2-19 months	Rhythmic arm actions: with audible / inaudible rattle, naturally-occurring	Naturally-occurring canonical babbling	<ul style="list-style-type: none"> • Infants shook rattles more up to and including the onset of canonical babbling, with a decrease after this stage (irrespective of hand used to shake rattle).
^a Eilers <i>et al.</i> (1993)	2 months +	Naturally-occurring rhythmic arm actions; motor milestones	Naturally-occurring canonical babbling	<ul style="list-style-type: none"> • Infants showed an increase in rhythmic hand banging in the lead up to the onset of canonical babbling, with a decrease after this stage.
Locke <i>et al.</i> (1995)	4-5 months, 6 months, 7 months, 8 months, 9 months	Rhythmic arm actions: with audible / inaudible rattle, naturally-occurring	Naturally-occurring canonical babbling	<ul style="list-style-type: none"> • Rattle shaking increased significantly up to the onset of babbling, with infants in the oldest pre-babbling group shaking the rattle more than those in the youngest pre-babbling group. • Rattle shaking also decreased significantly after the onset of babbling, with infants in the oldest pre-babbling group

	(cross-sectional)			shaking the rattle more than those in the youngest babbling group.
Libertus and Needham (2010)	3 months	Reaching and grasping toys using 'sticky mittens'	Looking time to experimenter (live context) / actor (televised context)	<ul style="list-style-type: none"> • Infants receiving active training with sticky mittens showed reduced looking times to the experimenter over a number of training sessions; infants receiving passive training showed no decrease. • These differences were evident in live but not televised contexts.
Libertus and Needham (2011)	3 months	Reaching and grasping toys using 'sticky mittens'	Face preference and face orienting (eye-tracking task)	<ul style="list-style-type: none"> • Infants receiving active training, but not passive training, with sticky mittens showed a face preference (looking time to face). 11 of 17 infants looked longer at the face in the active training condition, while 9 out of 18 infants looked longer at the face in the passive training condition. • Infants receiving active training, but not passive training, with sticky mittens oriented to the face first more often than the toy in a visual presentation. • Infants receiving active training showed the same pattern as untrained older infants (5 months). • Manual object exploration accounted for unique variance in face orienting behaviour, over and above other demographic and maturational factors.
Ejiri and Masataka (2001)	4-11 months	Naturally-occurring motor actions: handling, mouthing, banging, rhythmic	Naturally-occurring vocalisations, including canonical babbling	<ul style="list-style-type: none"> • Rhythmic actions peaked shortly before onset of canonical babbling, then decreased with age. • Vocalisations co-occurred more frequently with rhythmic actions than with other actions in the first 2 months of the observation period.

		action		<ul style="list-style-type: none"> • Co-occurring vocalisations differed from non co-occurring vocalisations in acoustic features, i.e., co-occurring vocalisations possessed the acoustic features of canonical babbling, while non co-occurring vocalisations did not.
Ejiri (1998)	5-9 months (within-subjects)	Rhythmic arm actions: with audible / inaudible rattle, naturally-occurring	Naturally-occurring canonical babbling	<ul style="list-style-type: none"> • Infants shook both types of rattles more up to and including the onset of canonical babbling, with a decrease after this stage. • Infants showed more naturally-occurring rhythmic hand movements around the onset of canonical babbling, with a decrease after this stage.
Clearfield (2011)	Exp. 1 9-11 months (between-subjects)	Exp. 1 Crawling / walking with baby walker in a designated space	Exp.1, Exp. 2, Exp. 3 Interaction time with mothers / experimenters / objects; gestures and vocalisations	Exp. 1 <ul style="list-style-type: none"> • No effect of locomotor status on interaction time, i.e., infants in both conditions spent longer interacting with objects than adults. • No effect of locomotor status on gestures and vocalisations, i.e., more undirected than directed gestures and vocalisations in both locomotor statuses.
	Exp. 2 9-12 months (between-subjects)	Exp. 2 Walking in a designated space (independent / with baby walker)		Exp. 2 <ul style="list-style-type: none"> • Infants in both conditions spent longer interacting with objects than adults, but this difference was relatively greater for independent walkers. • Independent walkers vocalised more than those in baby walkers.
	Exp. 3 9-14 months (within-subjects)	Exp. 3 Crawling / independent walking in a		<ul style="list-style-type: none"> • Independent walkers produced more directed gestures than those in baby walkers, but there was no difference in undirected gestures.

designated space

Exp. 3

- Infants in their 1st walking session interacted significantly more with mothers and significantly less with objects than those in their last crawling session or 2nd walking session.
- No effect of locomotor status on vocalisations.
- Infants produced significantly more gestures in their 1st walking session than in their last crawling session.
- Infants produced more directed gestures in their 1st and 2nd walking sessions than in their last crawling session.
- Infants produced significantly fewer undirected gestures in the 2nd compared to the 1st walking session.
- Walking 12-month-olds interacted significantly more with their mothers, produced more directed and fewer undirected gestures than crawling 12-month-olds, while there was no significant difference in vocalisations.

Clearfield *et al.*
(2008)

Exp. 1
9.5 months
and 14
months

Exp. 2
9-14 months
(within-
subjects)

Exp. 1, Exp. 2
Naturally-
occurring motor
activity: crawling
vs walking

Exp. 1
Naturally-
occurring social
behaviour: Look
frequencies to
parent /
experimenter face
during 10 min
unfamiliar play
session

Exp. 1

- Crawlers more likely to watch others communicate than walkers (independent of age).
- No significant differences between crawlers and walkers in other types of social look after age controlled.

Exp. 2

- Infants watched others interacting significantly more and engaged in significantly fewer social interaction bids in their last crawling session compared to their 1st walking session.
- Crawling 12-month-olds watched others interacting

Alcock and Krawczyk (2010)	18 months	Bayley Scales of Infant Development: gross / fine motor scales; Novel motor questionnaire: gross / fine motor scales	MacArthur-Bates Communicative Development Inventory - Production, Comprehension, Complexity scales	<p>significantly more and engaged in significantly fewer social interaction bids than walking 12-month-olds, while there were no significant differences in other types of social look.</p> <ul style="list-style-type: none"> • Gross motor questionnaire and fine motor questionnaire significantly correlated with CDI-Production and CDI-Comprehension, but not CDI-Complexity scales. • Gross motor questionnaire significant predictor of CDI-production, once cognitive ability controlled for and oral motor ability removed. • BSID motor score not correlated with any CDI scale.
Karasik <i>et al.</i> (2011)	11-13 months (within-subjects)	Naturally-occurring motor activity: crawling, walking	Naturally-occurring social behaviour: object sharing, social bids	<ul style="list-style-type: none"> • Infants increased the number of social bids involving objects with age, irrespective of whether they were crawling or walking. • 7/50 infants shared an object with their mothers at 11 months after travelling to them, and 6 of these 7 were walking at 13 months. • The number of total and stationary bids at 11 months did not significantly predict walking status at 13 months after controlling for crawling experience.
<i>Preschool / early years</i>				
Wang <i>et al.</i> (2012)	18 months - 3 years	Ages and Stages Questionnaire:	Ages and Stages Questionnaire:	<ul style="list-style-type: none"> • Structural Equation Modelling: <ul style="list-style-type: none"> - motor and communications skills significantly

	(within-subjects)	gross and fine motor scales	communication skills	<p>correlated</p> <ul style="list-style-type: none"> - early motor skills predicted later communication skills better than early communication skills predicted later motor skills - no significant differences in early motor skills and early communication skills in predicting later communication skills - early motor skills significantly better than early communication skills at predicting later motor skills
Piek <i>et al.</i> (2008)	3-5 years	McCarron Assessment of Neuromuscular Development (Neuromuscular Development Index)	Emotion Recognition Scales: Emotion Vocabulary Test, Emotion Comprehension Test, facial and vocal emotion recognition; Child Behaviour Checklist	<ul style="list-style-type: none"> • Significant correlation between Neuromuscular Development Index and emotion comprehension scores • NDI score not a significant predictor of emotion comprehension over and above age, verbal IQ and performance IQ.
Bart <i>et al.</i> (2007)	5-6 years (intake) 6-7 years (follow-up)	Developmental Test of Visual-Motor Integration; Fine Motor Accuracy Test; Visual-Spatial Perception Test;	Teacher reports: Child Behaviour Scale; Teacher-Child Rating Scale; Teacher Rating Scale of School	<ul style="list-style-type: none"> • General motor function (composite of motor tests) significantly correlated with disruptive behaviour, anxious-withdrawn behaviour, pro-social behaviour and school adaptation (teacher and child ratings). Strongest correlations with teacher-reported scholastic adaptation and disruptive behaviour. • Fine motor accuracy accounted for unique variance in

		test of muscle tone; Imitation of postures and Kinesthesia (Sensory Integration and Praxis Test)	Adjustment; Child Reports: Loneliness and Social Dissatisfaction Questionnaire; School Liking and Avoidance Scale; Pictorial Scale of Perceived Competence and Social Acceptance for Young Children	<p>scholastic adaptation (teacher report), but not in any of the other behaviours.</p> <ul style="list-style-type: none"> • General motor function was a significant predictor of disruptive behaviour, anxious-withdrawn behaviour and pro-social behaviour and teacher-reported school adjustment, but not child-reported school adjustment (once gender had been accounted for in the regression).
Cheng <i>et al.</i> (2009)	5-6 years	Movement Assessment Battery for Children	Peabody Picture Vocabulary Test-Revised (Chinese version); Language Ability Assessment for Preschoolers; Composite Speech/Language Tests	<ul style="list-style-type: none"> • MABC Total score significantly correlated with PPVT, LAAP and CSLT. • MABC Manual Dexterity scores accounted for a significant amount of variance in scores on language measures, over and above nonverbal intelligence and MABC Balance / Aiming and Catching.
Bar-Haim & Bart (2006)	5-6 years	Bruninks–Oseretsky Test of Motor Proficiency:	Play Observation Scale: play behaviour (Social play, social	<ul style="list-style-type: none"> • Children split into low, average and high motor ability. • The low motor ability group showed significantly less social play, and higher social reticence than children with

		balance; Kinesthesia Test; Imitation of Postures Test; Muscle tone assessment; The Developmental Test of Visual- Motor integration	reticence, solitary- passive play, solitary-functional play	average and high motor abilities. <ul style="list-style-type: none"> • No differences in amount of solitary-passive play between groups. • More children with low motor ability displayed solitary-functional behaviour than children with high motor ability, although this was only significant for outdoor play.
<i>School age</i>				
Ommundsen <i>et al.</i> (2010)	6-10 years (within- subjects)	Body Coordination Test for Children	Measure of social status with peers (child nominations of peers with whom to work / play)	<ul style="list-style-type: none"> • Motor ability at 6-7 years is significantly correlated with social status at 6-7 years, and with social status at 9-10 years. • Motor ability at 6-7 years accounted for unique variance in social status at 9-10 years • Motor ability and body mass index (weight status) at 6-7 years interacted significantly in predicting social status at 9-10 years <ul style="list-style-type: none"> - no significant difference in social status at 9-10 years between overweight and healthy-weight children with low motor ability at 6-7 years - social status at 9-10 years significantly lower for overweight than healthy-weight children with high motor ability at 6-7 years - overweight children with high motor ability at 6-7 years have significantly higher social status at 9-10 years than overweight children with low motor ability at 6-7 years.

^aOnly data from full-term infants reported here

Table 2. Studies investigating the relationship between motor and social abilities in infants and children with ASD, SLI and DCD

Reference	Age of participants	Groups	Motor behaviour task	Social behaviour task	Results
<i>Infancy</i>					
Bhat <i>et al.</i> (2012)	3, 6 and 18 months (prospective)	ASD at-risk	Alberta Infant Motor Scales	Mullen Scales of Early Learning	<ul style="list-style-type: none"> • Communication delay at 18 months was significantly associated with motor delay at 3 months <ul style="list-style-type: none"> - 50% of at-risk infants with a motor delay at 3 months had communication delay at 18 months - All of the at-risk infants with a communication delay at 18 months had a motor delay at 3 months • There was no significant association between motor delay at 6 months and communication delay at 18 months
Iverson and Wozniak (2007)	5-14 months (intake) 18 months (follow-up)	ASD at-risk vs low-risk (TD)	Naturally-occurring rhythmic motor actions	Naturally-occurring babbling vocalisations	<ul style="list-style-type: none"> • Both groups showed increase in rate of rhythmic arm movements from the month before babbling onset to babbling onset, with a decrease in rate of rhythmic arm movements after babbling onset. • This change in rate between sessions (i.e., increase up to babbling onset and decrease after babbling onset) was lower in at-risk than low-risk infants.

Gernsbacher <i>et al.</i> (2008)	Exp. 1 6-36 months (retrospective) 2-18 years (current)	Exp. 1 ASD	Exp. 1 Landmark-based parental-report interview: retrospective oral- motor, manual motor skills (parent report)	Exp. 1 Current speech fluency (assessment by professional)	Exp. 1 <ul style="list-style-type: none"> • Early manual motor skills differed in ASD group between those with minimally fluent and highly fluent speech, and between moderately fluent and highly fluent speech (i.e., those with highly fluent speech had significantly better manual motor skills than the 2 other groups).
Kim (2008)	2-5 years (current), using retrospective reports of language and motor milestones	ASD	Retrospective parent report: motor milestones; Vineland Adaptive Behavior Scales fine and gross motor scales	Retrospective parent report: language milestones; VABS receptive and expressive language scales	<ul style="list-style-type: none"> • VABS receptive language age significantly correlated with VABS Gross Motor age, but not with VABS Fine Motor age or retrospectively reported age of walking or crawling • VABS expressive language age not significantly correlated with VABS motor scores or retrospective motor milestones. • Reported age of babbling or first words not significantly correlated with retrospective motor milestones or VABS motor scores.
Leonard <i>et al.</i> (in press)	9 and 40 months (prospective) 5-7 years (follow-up)	ASD at-risk	Early visits: Mullen Scales of Early Learning, Vineland Adaptive Behavior Scales -	Follow-up visit: Social Communication Questionnaire; Autism Diagnostic Observation	<ul style="list-style-type: none"> • Children assigned to ‘motor difficulties’ and ‘typical motor’ groups based on VABS score at 9 and 40 months <ul style="list-style-type: none"> - the ‘poor motor’ group (9 months) had significantly poorer gaze and expression identification scores than the ‘typical

gross and fine motor scales

Follow-up visit:
Movement Assessment Battery for Children (2nd edition)

Schedule; Face processing: gaze, expression, speech sound identification, identity matching

motor' group, but not speech sound identification or identity matching scores, at 5-7 years.

- the two groups did not differ on face processing scores at 5-7 years when split at 40 months.
- the 'poor motor' group (40 months) had significantly higher social impairment scores on the SCQ than the 'typical motor' group, but not on the ADOS, at 5-7 years.
- the two groups did not differ on SCQ or ADOS scores at 5-7 years when split at 9 months

Preschool and early years

Sipes *et al.* (2011) 2 years

ASD vs PDD-NOS and Atyp

Batelle Developmental Inventory: gross and fine motor scaled scores

Baby and Infant Screen for Children with Autism Traits (Part 1)

- Children split into high and low gross and fine motor ability:
 - those in high gross motor ability groups had fewer impairments in socialisation
 - no significant differences between high and low fine motor ability groups in socialisation
 - level of fine motor skills affected socialisation more in the ASD group than in the other groups

Perry <i>et al.</i> (2009)	22-71 months	ASD	Vineland Adaptive Behavior Scales - Motor composite	Child Autism Rating Scale	<ul style="list-style-type: none"> • Motor skills standard scores and age equivalents significantly negatively correlated with autism severity • CARS autism severity scores did not account for variability in motor skills over and above age and IQ / mental age
Hsu <i>et al.</i> (2004)	3-4 years	ASD: split into groups based on social function <50%>	Chinese Children Developmental Inventory: gross motor, fine motor	Chinese Children Developmental Inventory: expressive language, concept comprehension, social comprehension, personal social function	<ul style="list-style-type: none"> • Gross and fine motor skills better than speech and social function in roughly 30% of both groups (i.e., those that showed poor compared to good social function). • Gross and fine motor developmental quotients significantly correlated with DQs of all other scales. • Gross and fine motor skills did not explain any unique variance in personal social function, over and above social comprehension scores.
Merriman <i>et al.</i> (1995)	4 years	SLI	Test of Gross Motor Development: locomotor / object control scores	Preschool Language Scale: auditory comprehension / verbal ability	<ul style="list-style-type: none"> • TGMD locomotor scores significantly correlated with PLS auditory comprehension and verbal ability scores. • No relationship between TMGD object control scores and PLS scales.
Paul and Fountain (1999)	20-34 months (intake); 7 years (follow-up)	SLI	Vineland Adaptive Behavior Scales: Gross / Fine	VABS: Receptive / Expressive Language; Language	<ul style="list-style-type: none"> • Discriminant analysis found that intake SES, VABS-Expressive Language and VABS-Gross Motor scores were significant predictors of DSS scores above 10th

			Motor	Development Survey: expressive vocabulary size; Phonetic inventory: number of consonant types produced; Developmental Sentence Scores: expressive language; spontaneous speech samples	percentile. <ul style="list-style-type: none"> • Motor scores were not significant predictors in linear regression models of DSS score.
Iverson and Braddock (2006)	2-6 years	SLI vs TD	Fine motor composite: Batelle Developmental Screening Inventory and Child Development Inventory	Language composite score: verbal utterance per minute, number of different words, mean length of utterance in morphemes (from observation).	<ul style="list-style-type: none"> • Fine Motor composite significantly correlated with language composite score in whole sample, and in SLI group only when sample split (increase in fine motor scores = increase in language composite score).
<i>School age</i>					
Vukovic <i>et al.</i> (2010)	4-7 years	SLI vs TD	McCarthy's Scales of Children's Abilities:	Boston Naming Test; Articulation Test; Token Test	<ul style="list-style-type: none"> • Significant correlations between coordination of legs with vocabulary and comprehension in the TD group, and with articulation in the SLI group

			Coordination of Legs / Arms; Test of Imitation of Movements		<ul style="list-style-type: none"> • Significant correlations between coordination of arms with vocabulary, comprehension and articulation in the TD group, but only with articulation in the SLI group
Dyck <i>et al.</i> (2007)	4-13 years	ASD	McCarron Assessment of Neuromuscular Development (Gross and Fine Motor Coordination)	Social Communication Questionnaire; Autism Diagnostic Interview	<ul style="list-style-type: none"> • Significant negative correlations between gross motor coordination and social impairments on ADI, and between fine motor coordination and social impairments on ADI (i.e., poorer motor scores = greater social impairment).
Jarus <i>et al.</i> (2011)	5-7 years	DCD vs TD	Movement Assessment Battery for Children	Children Assessment of Participation and Enjoyment; Activity preferences	<ul style="list-style-type: none"> • Children with lower motor scores carried out more social activities alone
Green <i>et al.</i> (2006)	5-10 years	DCD	Movement Assessment Battery for Children; Developmental Coordination Disorder Questionnaire	Strengths and Difficulties Questionnaire (parent questionnaire)	<ul style="list-style-type: none"> • No effect of degree of motor impairment on SDQ total scores. • MABC static and dynamic balance significantly correlated with SDQ emotional symptoms. • MABC ball skills significantly correlated with SDQ peer relations scale.

Wagner <i>et al.</i> (2012)	5-11 years	DCD vs TD	Movement Assessment Battery for Children	Intelligence and Development Scales (supplementary parent questionnaire): peer problems, internalising / externalising scales	<ul style="list-style-type: none"> • The greater the degree of motor impairment, the greater the degree of peer problems, and the greater the degree of internalising / externalising problems. • The relationship between internalising / externalising problems and DCD was mediated by degree of peer problems.
Schoemaker and Kalvaboer (1994)	6-9 years	DCD at-risk vs low-risk (TD)	Test of Motor Impairment	The Pictorial Scale of Perceived Competence and Social Acceptance for Young Children; Groningen Behavioral Checklist- School situation / Family situation (parent reports)	<ul style="list-style-type: none"> • TOMI motor scores significantly correlated with socially negative behaviour in both groups. <ul style="list-style-type: none"> - Negative correlation in DCD, positive correlation in low-risk • Motor scores predicted by introversion and socially negative behaviour scores, along with perceived physical competence and positive task orientation.
Cummins <i>et al.</i> (2006)	6-12 years	DCD at-risk vs low-risk (TD)	McCarron Assessment of Neuromuscular Development (Neuromuscular Development Index)	Emotion Recognition Scales (facial and vocal emotion); Child Behaviour Checklist: social problems scale	<ul style="list-style-type: none"> • Motor scores accounted for a significant amount of unique variance in social problems, over and above emotion recognition scores, age and IQ.

				(parent report)	
Hilton <i>et al.</i> (2007)	6-12 years	ASD (Asp) and TD	Movement Assessment Battery for Children	Social Responsiveness Scale	<ul style="list-style-type: none"> • Significant correlations between motor impairment level and <i>T</i>-scores on all SRS scales (Total score, social awareness, social cognition, social communication, social motivation, autistic mannerisms).
Webster <i>et al.</i> (2005)	7 years	SLI	Batelle Developmental Inventory: gross and fine motor scales	Batelle Developmental Inventory: communication scales; Peabody Picture Vocabulary Test; Expressive One-Word Picture Vocabulary Test-Revised; Vineland Adaptive Behavior Scales: communication	<ul style="list-style-type: none"> • BDI communication scores significantly correlated with BDI gross and fine motor scores
Dziuk <i>et al.</i> (2007)	8-14 years	ASD vs TD	Physical and Neurological Assessment of Subtle Signs	Autism Diagnostic Observation Schedule	<ul style="list-style-type: none"> • Basic motor skill was not a significant predictor of ADOS score (i.e., of social impairment severity).
Dyck <i>et al.</i> (2006)	Exp. 2 8-11 years	Exp.2 ASD vs DD vs TD	Exp. 2 McCarron Assessment of	Exp. 2 Theory of Mind tasks; Emotion	Exp. 2 <ul style="list-style-type: none"> • Significant correlations: fine motor

<p>Neuromuscular Development (Gross and Fine Motor Coordination)</p>	<p>Recognition Scales: Emotion Vocabulary Test, Comprehension Test, Unexpected Outcomes Test, facial and vocal emotion recognition</p>	<p>coordination with emotion recognition (TD, ASD, DD), emotion understanding (ASD, DD) and theory of mind scores (TD, ASD); gross motor coordination with emotion recognition (TD, ASD), emotion understanding (TD, ASD, DD) and theory of mind scores (TD, ASD, DD).</p> <ul style="list-style-type: none"> • Significantly stronger correlations in ASD group than in TD group: fine motor coordination and emotion understanding, fine motor coordination and theory of mind scores, gross motor coordination and emotion recognition, gross motor coordination and theory of mind scores. • When predicting theory of mind scores, significant unique contribution made by expressive language (TD group), gross motor coordination (DD group), fine motor coordination and perceptual organisation (ASD group). • When predicting emotion recognition scores, significant unique contribution made by expressive language, perceptual organisation and emotion understanding (TD group), but no unique contribution made by any factor in DD and ASD groups. 			
<p>Kanioglou <i>et al.</i> (2005)</p>	<p>10 years</p>	<p>DCD vs moderate</p>	<p>Movement Assessment</p>	<p>Sociometric assessment of</p>	<ul style="list-style-type: none"> • Children with moderate motor difficulties scored significantly lower than TD group on

Poulsen <i>et al.</i> (2011)	10-13 years	motor difficulties vs TD DCD	Battery for Children Movement Assessment Battery for Children	children's social status Questionnaire: participation in activities; Self Description Questionnaire; Loneliness and Social Dissatisfaction Questionnaire; Students' Life Satisfaction Scale	social acceptance and social preference, and significantly higher on social rejection. <ul style="list-style-type: none"> • Classification and regression tree (CART) analysis identified different groups based on their combinations of scores from the various tests: <ul style="list-style-type: none"> - 3 groups based on poor motor ability on one or more MABC subtests - 1 group with relatively better motor ability on MABC (total score) but still poor fundamental movement skills, with high levels of participation in structured, adult-supervised activities - 1 group with relatively better motor ability on MABC (total score) but poor manual dexterity and ball skills, with low participation in informal physical activities with friends, and poor peer relations.
Hilton <i>et al.</i> (2011)	4-20 years	ASD and siblings concordant / discordant	Bruininks-Oseretsky Test of Motor Proficiency (2 nd Edition); Developmental Coordination Disorder Questionnaire	Social Responsiveness Scale	<ul style="list-style-type: none"> • Total social responsiveness scores significant predictor of motor scores, over and above age, gender and ethnicity. • In children with ASD, motor scores significantly inversely correlated with degree of social impairment, for total scores and individual subtests.

(2007)
