Research in Developmental Disabilities 39 (2015) 32–42

Contents lists available at ScienceDirect

Research in Developmental Disabilities

Motor functioning, exploration, visuospatial cognition and language development in preschool children with autism

Annika Hellendoorn [a,*], Lex Wijnroks [a], Emma van Daalen [b], Claudine Dietz [d], Jan K. Buitelaar [c], Paul Leseman [a]

[a] Department of Special Education: Centre for Cognitive and Motor Disabilities, Heidelberglaan 1, P.O. Box 80.140, 3508 TC Utrecht, The Netherlands
[b] Department of Child and Adolescent Psychiatry, University Medical Centre Utrecht, The Netherlands
[c] Department of Cognitive Neuroscience, Donders Institute for Brain, Cognition and Behavior, Radboud University Nijmegen, and Karakter Child and Adolescent Psychiatry University Centre, Nijmegen, The Netherlands
[d] Youth Division, Altrecht Institute for Mental Health Care, Utrecht, The Netherlands

ARTICLE INFO

Article history:
Received 17 August 2014
Received in revised form 17 December 2014
Accepted 19 December 2014
Available online 28 January 2015

Keywords:
Autism
Fine motor functioning
Exploration
Visuospatial cognition
Language

ABSTRACT

In order to understand typical and atypical developmental trajectories it is important to assess how strengths or weaknesses in one domain may be affecting performance in other domains. This study examined longitudinal relations between early fine motor functioning, visuospatial cognition, exploration, and language development in preschool children with ASD and children with other developmental delays/disorders. The ASD group included 63 children at T1 (*M*age = 27.10 months, *SD* = 8.71) and 46 children at T2 (*M*age = 45.85 months, *SD* = 7.16). The DD group consisted of 269 children at T1 (*M*age = 17.99 months, *SD* = 5.59), and 121 children at T2 (*M*age = 43.51 months, *SD* = 3.81). A subgroup nested within the total sample was randomly selected and studied in-depth on exploratory behavior. This group consisted of 50 children, 21 children with ASD (*M*age = 27.57, *SD* = 7.09) and 29 children with DD (*M*age = 24.03 months, *SD* = 6.42). Fine motor functioning predicted language in both groups. Fine motor functioning was related to visuospatial cognition in both groups and related to object exploration, spatial exploration, and social orientation during exploration only in the ASD group. Visuospatial cognition and all exploration measures were related to both receptive and expressive language in both groups. The findings are in line with the embodied cognition theory, which suggests that cognition emerges from and is grounded in the bodily interactions of an agent with the environment. This study emphasizes the need for researchers and clinicians to consider cognition as emergent from multiple interacting systems.

1. Introduction

Autism spectrum disorder (ASD) is a pervasive neurodevelopmental disorder characterized by impairments in social interaction and communication, co-occurring with restricted patterns of interest and repetitive behaviors (American Psychiatric Association, 2000). Current ASD theories, such as the Theory of Mind (ToM) theory (Baron-Cohen, Leslie, & Frith,

* Corresponding author. Tel.: +31 30 2534963.
E-mail address: A.Hellendoorn@uu.nl (A. Hellendoorn).

http://dx.doi.org/10.1016/j.ridd.2014.12.033
0891-4222/

1985) and the Executive Dysfunction hypothesis (Ozonoff, Pennington, & Rogers, 1991) have increased the understanding of ASD significantly, but are less able to account for complex interactions across developmental domains. In studying ASD, other developmental disorders and typical development, it is important not to be restricted to phenotypic outcomes to draw conclusions about impaired modules in the initial state, but rather to take a developmental approach and examine the course of the disorder over time, including the role of developmental cascades across domains (López, 2013; Masten & Cicchetti, 2010; Paterson, Brown, Gsödl, Johnson, & Karmiloff-Smith, 1999; Smith, 2013).

The theory of embodied cognition proposes that cognition emerges in the interaction between an agent and its environment and as a result of sensorimotor activity (Smith & Gasser, 2005; Thelen, 2000b). According to this account motor abilities and exploration create opportunities for learning (Gibson, 1988; Gibson & Pick, 2000; Thelen, 2000a). Thereby this theory emphasizes the active role children play in their own development (Smith, 2005a; Smith & Gasser, 2005). The emergence of language, an important developmental milestone, is a multifaceted embodied process that is significantly influenced by the interaction of the child with its environment (Hockema & Smith, 2009; Iverson, 2010; Wellsby & Pexman, 2014). While there is considerable heterogeneity in the pattern of language skills found in children with ASD (Kjelgaard & Tager-Flusberg, 2001), several studies indicate the presence of language delays and impairments in ASD (Eigsti, Marchena, Schuh, & Kelley, 2011; Howlin, 2003). According to an embodied cognition framework it is important to consider the role of sensorimotor processes in the language development of children with ASD.

Various researchers have noted delays and deficits in fine and gross motor skills in young children with ASD or at risk for ASD across all ages and levels of functioning (Bhat, Landa, & Cole, 2011; Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Gernsbacher, Sauer, Geye, Schweigert, & Goldsmith, 2008; Landa & Garret-Mayer, 2006; LeBarton & Iverson, 2013; Lloyd, MacDonald, & Lord, 2013; Provost, Lopez, & Heimerl, 2007). Theoretical considerations and empirical studies indicate that motor skills play an important role in the development of language (Fischer & Zwaan, 2008; Hill, 2001; Iverson, 2010; Iverson & Thelen, 1999; Thelen, 2000a). Neurological studies also suggest that language is grounded in sensorimotor processes (Glenberg & Kaschak, 2002; Pulvermüller, 2005; Pulvermüller & Fadiga, 2010).

With the exception of some studies (Gernsbacher et al., 2008; LeBarton & Iverson, 2013; Stone & Yoder, 2001), longitudinal studies that directly examine the developmental relationship between motor functioning and language development in ASD are lacking. Moreover, the mechanisms underlying the relationship between motor functioning and language development in ASD have not been examined so far and are unknown. Several authors have stressed the need for research that clarifies the relationship between motor impairments and delays and deficits in language development seen in ASD (LeBarton & Iverson, 2013; Provost et al., 2007).

Interaction with both the physical and the social world is important for the acquisition of language (Hockema & Smith, 2009; Iverson, 2010). There has to be an awareness of the world before it can be put into words. In other words, a conceptual basis is required to learn language in a meaningful way (Antonucci & Alt, 2011; McDonough, Choi, & Mandler, 2003; Gibson, 1979). A child becomes aware of the world through exploration, the process in which a child actively obtains information about the environment and learns about the action possibilities (i.e. the affordances) that the environment offers (Gibson, 1979, 1988; Smith & Gasser, 2005). Active exploration is positively related to attention (Perone, Madole, Ross-Sheehy, Carey, & Oakes, 2008), recognition (Harman, Humphrey, & Goodale, 1999; Pereira, James, Jones, & Smith, 2008), perception (Needham, 2000), memory (Liu, Ward, & Markall, 2007; Meijer & Van der Lubbe, 2011), and categorization (Sasaoka, Asakura, & Kawahara, 2010) of objects. Several studies have demonstrated that sensorimotor experience and the resulting improved object and affordance perception are positively related to the development of language (Antonucci & Alt, 2011; Jones & Smith, 2005; Lee, 1993; Lifter & Bloom, 1989; Ruff, McCarton, Kurzberg, & Vaughan, 1984; Scofield, Hernandez-Reif, & Keith, 2009; Smith & Gasser, 2005; Smith, 2003, 2005b, 2013). These effects are found for nouns, verbs and adjectives (Wellsby & Pexman, 2014). Smith (2003) demonstrated for instance that the ability to recognize objects from sparse geometric models of 3-dimensional object shape is linked to children's object name vocabulary size. These findings have been replicated several times (Jones & Smith, 2005; Pereira & Smith, 2009; Son, Smith, & Goldstone, 2008). Object exploration also provides the opportunity to extract information that is important for the acquisition of categorical knowledge (Smith, 2005a,b; Smith & Gasser, 2005). In the early lexicon, similarity in shape is for instance important for the formation of categories (Samuelson & Smith, 1999). Learning about categories is important for language development (Ruff et al., 1984). Another study also shows that manual experience with an object facilitates the ability to name the object (Yee, Chrysikou, Hoffman, & Thompson-Schill, 2013). Exploration may also contribute to language development by facilitating social interaction and by eliciting language promoting behaviors of parents (Clearfield, Osborne, & Mullen, 2008). As children begin to explore objects, parents increasingly promote and partake in interactions with their child (Bornstein & Tamis-LeMonda, 1990). Choi (2000) found that nouns en verbs are often mentioned at moments when children are manipulating toys.

Young typically developing children spent a large amount of time engaged in a variety of exploratory behaviors, tailoring their actions to an object's properties and properties of the environment (Bourgeois, Khawar, Neal, & Lockman, 2005; Rochat, 1989; Ruff, 1984). Children with ASD are deviant in their exploration. They display more rotating, spinning, and unusual visual exploration, and stereotyped, repetitive and restricted uses of objects (Baranek, 1999; Bruckner & Yoder, 2007; Ozonoff et al., 2008; Wetherby et al., 2004; Williams, Costall, & Reddy, 1999), and spent less time in exploration (Koterba, Leezenbaum, & Iverson, 2012; Pierce & Courchesne, 2001) than children with developmental delays and typically developing children. Children with ASD also often explore within a single modality, such as visually fixating on an object (Zwaigenbaum et al., 2005), which limits the multimodal input. As described above, studies suggest that exploration is related to language development. Thus, reduced and less effective exploration may limit subsequent language development. Reduced exploration at 7 and 9 months is indeed related to poor language outcomes at 2 year in preterm infants (Ruff et al., 1984). Thus far, it is not known whether the exploration of children with ASD is predictive of their language development.

Studies suggest that language development may also be related to visuospatial skills. Preverbal infants already develop spatial knowledge such as understanding containment and support that they use to comprehend the language they hear (McDonough et al., 2003). Understanding prepositions (Karmiloff & Karmiloff-Smith, 2001), demonstratives (Küntay & Özyürek, 2006), verbs (Richardson, Spivey, Barsalou, & McRae, 2003), and narratives (Humphries, Cardy, Worling, & Peets, 2004) requires visuospatial understanding. In accordance with these results, studies demonstrate that children with specific language impairment perform at a lower level than typically developing children on visuospatial tasks (Bavin, Wilson, Maruff, & Sleeman, 2005; Hick, Botting, & Conti-Ramsden, 2005; Kamhi, Catts, Mauer, Apel, & Gentry, 1988; Marton, 2008).

Results regarding visuospatial abilities in ASD are inconsistent. Some studies report superior visuospatial functioning in ASD (Mitchell & Ropar, 2004; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001), other demonstrate intact visuospatial cognition (Edgin & Pennington, 2005), but deficits in visuospatial abilities are also found, such as fragmented visuospatial processing compared to children with developmental delays and typically developing children (Kuschner, Bennetto, & Yost, 2007; Schlooz et al., 2006; Vlamings, Jonkman, van Daalen, van der Gaag, & Kemner, 2010). One study suggests that people with autism exhibit both enhanced and diminished visual processing on the same task, depending on the complexity of the stimuli (Bertone, Mottron, Jelenic, & Faubert, 2005). The question is whether early visuospatial abilities of children with ASD are predictive of their later language development.

Both exploration and visuospatial cognition may be partially dependent upon motor skills. Several authors suggest that motor skills constrain and guide the development of other skills (Gibson, 1988; Thelen, 2000a,b). Motor skills facilitate exploration (Campos et al., 2000; Clearfield, 2011; Gibson, 1988; Soska, Adolph, & Johnson, 2010) and the development of visuospatial skills (Campos et al., 2000; Clearfield, 2004; Jansen-Osmann, Wiedenbauer, & Heil, 2008). Fine motor skills, such as unilateral reaching and independent use of the hand and arms in relation to one another, are also important for exploration (Gibson, 1988; Iverson, 2010) and visuospatial cognition (Soska et al., 2010). Between the ages of eight months and two years, children for instance develop in their exploratory behaviors from 'separations', a relatively simple motor task, to 'constructions' (e.g. stringing beads), which requires more sophisticated motor skills (Lifter & Bloom, 1989). Fine motor skills also facilitate the development of visuospatial cognition. The ability to perform three dimensional object completion, in other words, the ability to perceive an object as a complete volume in visual space despite only seeing it from a limited viewpoint, is dependent upon sophisticated manual motor skills, such as rotating objects or transferring objects to perceive their unseen backs (Soska et al., 2010). Another example is the ability to seriate, insert or stack a set of nesting cups or boxes. Through these experiences the child may discover the meaning of containment of support. Thus, the acquisition of motor skills facilitates exploratory behaviors and visuospatial skills (Soska et al., 2010).

To summarize, studies suggest that language development may be facilitated by exploration and visuospatial cognition. Both exploration and visuospatial cognition seem to be (partly) dependent on motor skills. It is known that children with ASD differ in their motor development, exploration and visuospatial cognition in comparison to typically developing children and children with developmental delays without ASD. However, thus far no study has examined whether early difficulties in motor functioning of children with ASD may predict their language development and whether this relationship is mediated by exploration and visuospatial cognition. Moreover, information is needed as to what extent the proposed longitudinal relationships are specific to ASD.

1.1. The present study

The aims of the present longitudinal study were to examine whether (1) early fine motor functioning is predictive of later receptive and expressive language development in children with ASD and children with other developmental delays/ disorders (DD), (2) exploration and visuospatial cognition are mediators of the relationship between fine motor functioning and language in children with ASD and children with DD and (3) the proposed relationships are different for children with ASD and children with DD i.e. whether the relationships are moderated by diagnostic status.

2. Methods

2.1. Procedure

As part of a large study (ScreeningsOnderzoek Sociale Ontwikkeling, SOSO) into the early signs of ASD conducted by the University Medical Center Utrecht (UMCU), The Netherlands, 31.724 children aged 14–15 months from the general population in the province of Utrecht, were screened at well-baby clinics with the Early Screening of Autistic Traits (ESAT; Dietz, Swinkels, Van Daalen, Van Engeland, & Buitelaar, 2006; Swinkels et al., 2006) using a two-level screening procedure. Children were pre-screened at age 14–15 months using the 4-item ESAT. Children that pre-screened positive (failing one or more of the four items) were evaluated during a home visit using the 14-item screening instrument ESAT. Children who failed at least 3 items of the 14-item ESAT were considered screen positive and were further assessed by means of diagnostic and cognitive measures at two measurements points. Screening and testing procedures were approved by the Medical Ethics Review Board of the UMCU.

2.2. Participants

All participants were recruited from the screening study for ASD in Utrecht. From the children that screened positive on the ESAT two groups of children were randomly selected for the present study: children diagnosed with ASD and children with other developmental delays/disorders (DD) of mixed etiology. Of this latter group none had a current or previous clinical or DSM-IV diagnosis of ASD and none met the criteria for ASD on the Autism Diagnostic Interview-Revised (Lord, Rutter, & Le Couteur, 1994) or Autism Diagnostic Observation Schedule-Generic (Lord et al., 1989, 2000). The DD group was heterogeneous, including children with global developmental delays of unknown etiology, children with a language disorder, and children with attention-deficit/hyperactivity disorder. The ASD group included 63 children, 49 boys and 14 girls, at T1 (*M*age = 27.10 months, *SD* = 8.71) and 46 children, 38 boys and 8 girls, at T2 (*M*age = 45.85 months, *SD* = 7.16). The DD group consisted of 269 children, 196 boys and 73 girls, at T1 (*M*age = 17.99 months, *SD* = 5.59), and 121 children, 95 boys and 26 girls, at T2 (*M*age = 43.51 months, *SD* = 3.81). A subgroup nested within the total sample was randomly selected and studied in-depth on exploratory behavior. This group consisted of 50 children, 21 with ASD (*M*age = 27.57, *SD* = 7.09), 16 boys and 5 girls, and 29 with DD (*M*age = 24.03 months, *SD* = 6.42), 21 boys and 8 girls. Matching groups on mental age were not possible, since both non-verbal (motor functioning and visuospatial cognition) and verbal IQ (expressive and receptive language) are the variables studied in the current study. Results of attrition analysis are reported in the data analysis section.

2.3. Measures

Diagnostic assessments for ASD. The diagnostic assessments consisted of a standardized parental interview with the Autism Diagnostic Interview-Revised (ADI-R; Lord et al., 1994), a standardized behavior observation using the Autism Diagnostic Observation Schedule-Generic (ADOS-G; Lord et al., 2000), the Mullen Scales of Early Learning (MSEL; Mullen, 1995) and pediatric and medical examination.

Fine motor and cognitive measures. The Mullen Scales of Early Learning (MSEL; Mullen, 1995) were used to assess fine motor functioning, visuospatial cognition, receptive language and expressive language. This measure was administered by trained psychologists. The gross motor scale of the MSEL was not administered in the present study. The MSEL is a standardized individually administered measure of cognitive functioning for preschool children up to 68 months (Mullen, 1995). Since the use of age equivalent scores in the MSEL has been recommended for young children with ASD (Akshoomoff, 2006), these scores were used in this study. The MSEL are suitable for assessing children with ASD (Akshoomoff, 2006).

Exploration. To assess exploration an observation coding scheme was developed for this study based on the literature. The 'breadth' scale is based on the idea that it is important take into account the variability in children's exploration patterns (Pierce & Courchesne, 2001), including the fact that different objects have different affordances (Bourgeois et al., 2005; Gibson, 1979). The 'depth' scale focuses more on the importance of integrating multimodal information and attentiveness (Rochat, 1989). Since studies indicate that making combinations with objects is an important developmental step (Lifter & Bloom, 1989) a 'combinatorial' scale was included. It is well-known that children with ASD may exhibit atypical exploratory behavior (e.g. Ozonoff et al., 2008), therefore an 'atypical' scale is also part of the coding scheme. Finally, a 'social orientation' scale was included to take into account a social component within the exploration process. The final coding scheme consisted of nine scales. The *Breadth of Fine motor Object Exploration scale* focuses on whether the child was interested in a variety of objects and whether the affordances of the small objects (e.g., a pushing button) elicit the 'appropriate' reaction of the child (e.g., pushing the button). The *Depth of Fine motor Object Exploration scale* refers to whether the child displayed focused-attentive exploration of small objects, while integrating sensory (e.g. visual, auditory) information. The *Combinatorial Fine motor Object Exploration scale* describes whether the child assembled small objects (e.g. piling or inserting). The *Atypical Fine motor Exploration scale* measures whether the child explored or manipulated small objects in an unusual manner, that is in a narrow or one-sided, repetitive way, within basically one sensory modality, without apparent joy and/or focused attention, and/or by reacting inappropriately (or not at all) to the affordances of objects. An example is repetitively rotating toys. The *Breadth of Gross Motor Spatial Exploration scale* assesses whether the child was attracted by the various affordances of the room/space and the bigger objects in the room (e.g., looking in the mirror) in a goal-directed way. The *Depth of Gross Motor Spatial Exploration scale* refers to whether the child showed focused-attentive exploration of the room/space and/or the bigger objects in the room, while integrating sensory information. The *Combinatorial Gross Motor Spatial Exploration scale* describes whether the child assembled or combined big objects in the room or attempts to reorder the spatial lay-out (e.g., putting a chair in front of the closet to retrieve something). The *Atypical Gross Motor Exploration Scale* refers to whether the child explored the room/space and/or big objects in an unusual way, that is, in a narrow or one-sided, repetitive way, within basically one sensory modality, without apparent joy and/or focused attention, and/or by reacting inappropriately (or not at all) to the affordances of the room/space and/or big objects. An example is looking at oneself in the mirror from an unusual angle. Finally, the *Social Orientation Exploration scale* assesses whether the child shared interests and experiences with other persons.

A seven-point Likert scale ranging from '*not present*' to '*extremely present*' was used for scoring. Three exploration scores were derived from the coding scheme: object exploration (four items: breadth, depth, combinatorial, and atypical), spatial exploration (four items: breadth, depth, combinatorial, and atypical) and social orientation during exploration (one item). These scores were computed by calculating the sum of the unweighted items. The two 'atypical exploration' scales were reversely coded with a high score on these scales representing a low score on exploration. To investigate the factor structure of the 9-item observation coding scheme, a confirmatory factor analysis was conducted with AMOS 18.0 which resulted in a good fit with $\chi^2 = 30.19$, $df = 24$, $p = .18$, RMSEA = .08, TLI = .95, CFI = .97 (Browne & Cudeck, 1993; Kline, 1998). All standardized path coefficients were significant at the .05 level (except one which had a p-value of .08) and ranged between .25 and .99. Internal consistency as measured with Cronbach's α *was .85 for the subscale of object exploration, and .72 for the subscale of spatial exploration.* The exploration observation scheme was applied to videotaped observations of the ADOS-G (Lord et al., 2000). All assessments were standardized and completed in the same laboratory with the same toys and objects available. The child's primary caregiver sat in a chair in the room during the assessment. Exploration was coded in a blind procedure by two trained observers unaware of the diagnoses of the children. Since the categories of the scale are ordinal and partial agreement had to be taken into account, a weighted kappa (linear weights) was used resulting in a kappa of .65, 95% CI [.60, .70]. This is generally considered to be good agreement (Altman, 1991). Discrepancies between raters were discussed and resolved at a consensus meeting.

2.4. Data analysis

The mediation (Preacher & Hayes, 2004) and moderated mediation approach (Preacher, Rucker, & Hayes, 2007) were used to test the different hypotheses in the present study. More specifically, to examine whether early fine motor functioning is predictive of receptive and expressive language development, and whether exploration and visuospatial cognition are mediators of the relationship between fine motor functioning and language, a SPSS macro developed by Preacher and Hayes (2008) was used. This approach was used because it incorporates a bootstrap procedure, which is considered to be a very powerful test of indirect (mediation) effects. Bootstrapping is a resampling procedure. In bootstrapping, the sample is conceptualized as a pseudo-population that represents the broader population from which the sample was derived, and the sampling distribution of any statistic can be generated by calculating the statistic of interest in multiple resamples of the data set (Preacher & Hayes, 2004). This approach is considered superior to other methods; it produces a test that can be applied to small samples with more confidence and it circumvents the power problem caused by asymmetries and other forms of nonnormality in the sampling distribution of the indirect effect (Preacher & Hayes, 2004). In the current study, 5000 bootstrap resamples were used to generate bias corrected and accelerated 95% confidence intervals.

In addition to the mediation effect, it is possible that the strength of the hypothesized relationships including the mediation effect is conditional on the value of the moderator, i.e. whether the relationships are different for children with ASD compared to children with DD, in other words, whether these relationships are *moderated* by diagnostic status. To answer this research question, again an SPSS macro designed by Preacher et al. (2007) was used. This macro provides a method for examining the influence of the moderator variables on the relationships. Chronological age was included as a covariate in the analyses.

Attrition analysis with Chi-square tests and ANOVAs revealed that children who did not participate in the second measurement wave were more often in the DD group than in the ASD group ($p < .05$), were more often male ($p < .05$) and had higher scores on all motor and cognitive measures at T1 ($p < .05$).

3. Results

3.1. Group differences

Descriptive information per group can be found in Table 1. In addition to the raw means, adjusted means controlled for age are reported since age differences between groups were found to be significant at both time points, with $F(1,330) = 106.82$, $p < .001$, at T1 and $F(1,165) = 7.42$, $p < .01$, at T2. For the exploration measures only raw means are reported since age differences were not significant between the ASD and DD children in that subgroup ($p = .07$). ANCOVAs were conducted to evaluate group differences between the ASD group and the DD group. Group differences were found on all variables of interest ($p < .05$). Effect sizes were interpreted according to Cohen (1988). As can be seen in Table 1, the ASD group scored lower than the DD group on fine motor functioning and visuospatial cognition at T1, which are both medium effects. For receptive and expressive language at T2, the ASD group also scored lower than the DD group, with a small effect for receptive language and a medium effect for expressive language. With regard to exploration, the ASD group scored lower than the DD group on all measures, with a medium effect for object and spatial exploration and a large effect for social orientation during exploration.

3.2. Interrelationships among study variables

The results of the analyses are presented in Table 2. The first column is the effect of the independent variable fine motor functioning on the mediator, which is visuospatial cognition or one of the exploration measures. The effect of the mediator on the dependent variable (receptive or expressive language) is displayed in the second column. The third column is the direct effect of the independent variable on the dependent variable, controlling for the effect of the mediator. The indirect effect of the independent variable on the dependent variable through the mediator can be found in the fourth column. The fifth column is the total effect of the independent variable on the dependent variable. Finally, the last column (Adj.R^2)

Table 1
Descriptive statistics for the ASD group and the DD group at T1 and T2.

	ASD[a]		DD[b]		Partial η^2
	Raw *M*	Adjusted *M*	Raw *M*	Adjusted *M*	
Fine motor functioning T1	20.21 (6.05)	15.85 (0.52)	18.56 (5.02)	19.59 (0.23)***	.11
Fine motor functioning T2	40.87 (9.24)	39.66 (1.12)	41.74 (7.83)	42.21 (0.68)	–
Visuospatial cognition T1	20.32 (7.20)	15.53 (0.59)	17.73 (5.49)	18.85 (0.26)***	.07
Visuospatial cognition T2	46.16 (9.60)	45.00 (1.24)	44.77 (8.66)	45.21 (0.76)	–
Receptive language T1	16.04 (8.45)	11.28 (0.64)	15.36 (5.38)	16.48 (0.29)***	.13
Receptive language T2	37.33 (6.56)	36.78 (0.96)	38.81 (6.58)	39.02 (0.58)*	.02
Expressive language T1	17.02 (8.61)	12.79 (0.63)	15.55 (4.80)	16.54 (0.28)***	.08
Expressive language T2	36.49 (6.89)	35.99 (1.19)	41.74 (8.43)	41.93 (0.73)***	.10
Object exploration[c]	15.76 (3.18)	–	17.79 (2.78)*	–	.11
Spatial exploration[c]	12.57 (1.66)	–	14.03 (2.56)*	–	.10
Social orientation during exploration[c]	3.62 (0.67)	–	4.28 (0.70)**	–	.19

Note: Scores are raw means (standard deviations) and adjusted means (standard errors) controlled for age. T1 and T2 refer to the first and second measurement point respectively.
[a] T1, $n = 63$, T2, $n = 46$ (ASD).
[b] T1, $n = 269$, T2, $n = 121$ (DD).
[c] Measure was calculated for a subgroup of children: ASD: $n = 21$, DD: $n = 29$, scores were not controlled for age since age differences between the groups were not significant for this subgroup.
* $p < .05$ (group differences).
** $p < .01$ (group differences).
*** $p < .001$ (group differences).

displays the variance in the dependent variable that is explained by the mediator and the independent variable. It should be noted that Table 2 shows unstandardized coefficients. Fig. 1 provides a visual overview of the results.

Positive relations between fine motor functioning at T1 and receptive and expressive language at T2 were found in the ASD group and the DD group, controlling for age, meaning that higher scores on early fine motor functioning predict higher scores on later receptive and expressive language (total effects in Table 2). Regarding the moderation of these relationships, the interaction term between group and fine motor functioning on receptive language was not significant. This means that the relation between fine motor functioning and receptive language was not different in the ASD compared to the DD group. For expressive language however, the interaction term between fine motor functioning and group was significant ($B = -0.50$, $t = -2.22$, $p = 0.03$) with a stronger relationship in the ASD group ($B = 1.18$, $t = 5.52$, $p < .001$) compared to the DD group ($B = 0.67$, $t = 4.67$, $p < .001$). The interaction term is negative because the ASD group was coded as 1 and the DD group as 2.

Visuospatial cognition. Fine motor functioning is related to visuospatial cognition and visuospatial cognition is related to both language measures in both groups. Furthermore, indirect effects of fine motor functioning on both receptive and expressive language through visuospatial cognition were found in both groups. The strength of the relationship between fine motor functioning and visuospatial cognition, and the strength of the relationships between visuospatial cognition and language were not moderated by group.

Exploration. For object exploration, results indicate that fine motor functioning is related to object exploration only in the ASD group and that object exploration is related to both language measures in both groups. For the ASD group an indirect effect was found of fine motor functioning on both receptive and expressive language through object exploration. Although this mediation effect of object exploration was not found in the DD group, there was an effect of object exploration on both language measures in this group. These relationships were not moderated by group.

For spatial exploration, an effect of fine motor functioning on spatial exploration was found only in the ASD group. A relationship between spatial exploration and expressive language was found in both groups. This relationship was not moderated by group. In the ASD group an indirect effect of fine motor functioning on expressive language through spatial exploration was found. No relationship was found between spatial exploration and receptive language in both groups.

Regarding the social orientation during exploration, an effect of fine motor functioning on social orientation during exploration was also found only in the ASD group. The relationships between social orientation during exploration and both language measures were present in both groups. Only in the ASD group an indirect effect of fine motor functioning on both language measures through social orientation during exploration was found. The relationship between social orientation during exploration and expressive and receptive language was not moderated by group.

4. Discussion

This longitudinal study demonstrates that early fine motor functioning is a predictor of later receptive and expressive language development of children with ASD and children with other developmental delays/disorders. Furthermore, through mediator–moderator analyses this study provides the first evidence that exploration and visuospatial cognition are mediators of the relationships between fine motor functioning and language, and that some of these relationships are moderated by diagnostic status with stronger relationships between variables in the ASD group compared to the DD group.

Table 2
Analysis of the relationship between fine motor functioning T1 and language T2 per group.

DV	Receptive language						Expressive language					
Groups	Effect of IV on M	Effect of M on DV	Direct effect IV on DV	Indirect effect IV on DV [CI]	Total effect IV on DV	Adj. R^2	Effect of IV on M	Effect of M on DV	Direct effect IV on DV	Indirect effect IV on DV [CI]	Total effect IV on DV	Adj. R^2
Visuospatial cognition (M)												
ASD	0.84***	0.73**	0.23	**0.59 [0.26, 1.09]**	0.84***	0.46	0.84***	0.61**	0.46*	**0.51 [0.16, 1.14]**	0.97***	0.58
DD	0.72***	0.47**	0.38*	**0.34 [0.07, 0.59]**	0.72***	0.32	0.72***	0.76***	0.33	**0.56 [0.19, 0.91]**	0.88***	0.30
Object exploration (M)												
ASD	0.38*	1.16*	0.40	**0.41 [0.07, 1.23]**	0.85**	0.44	0.38*	0.67*	0.84***	**0.22 [0.02, 0.66]**	1.10***	0.74
DD	0.14	0.89*	0.81**	0.11 [−0.28, 0.64]	0.94**	0.38	0.14	1.47**	0.92*	0.19 [−0.45, 0.97]	1.13**	0.41
Spatial exploration (M)												
ASD	0.22***	2.59	0.27	0.47 [−0.002, 1.43]	0.85**	0.37	0.22***	1.84*	0.69*	**0.39 [0.03, 0.91]**	1.10***	0.75
DD	0.16	0.80	0.81**	0.11 [−0.01, 0.58]	0.94**	0.31	0.16	1.43*	0.89*	0.20 [−0.02, 1.00]	1.13**	0.34
Social orientation exploration (M)												
ASD	0.12***	7.38**	−0.02	**0.80 [0.30, 3.16]**	0.85**	0.51	0.12***	4.92**	0.52*	**0.57 [0.28, 1.43]**	1.10***	0.80
DD	0.01	3.02	0.92**	0.04 [−0.25, 0.40]	0.94**	0.33	0.01	5.88**	1.09**	0.09 [−0.41, 0.62]	1.13**	0.40

Note: Results are based on 5000 bootstrap samples. Bias corrected 95% confidence intervals reported between straight brackets. Indirect effects that are statistically significant are printed in bold. The coefficients are unstandardized values. IV, independent variable (fine motor functioning); M, mediator (visuospatial cognition/exploration measures); DV, dependent variable (receptive or expressive language); CI, confidence interval. Visuospatial cognition analyses: ASD, n = 46, DD, n = 121. Exploration analyses: ASD, n = 20, DD, n = 29.

* $p < .05$.

** $p < .01$.

*** $p < .001$.

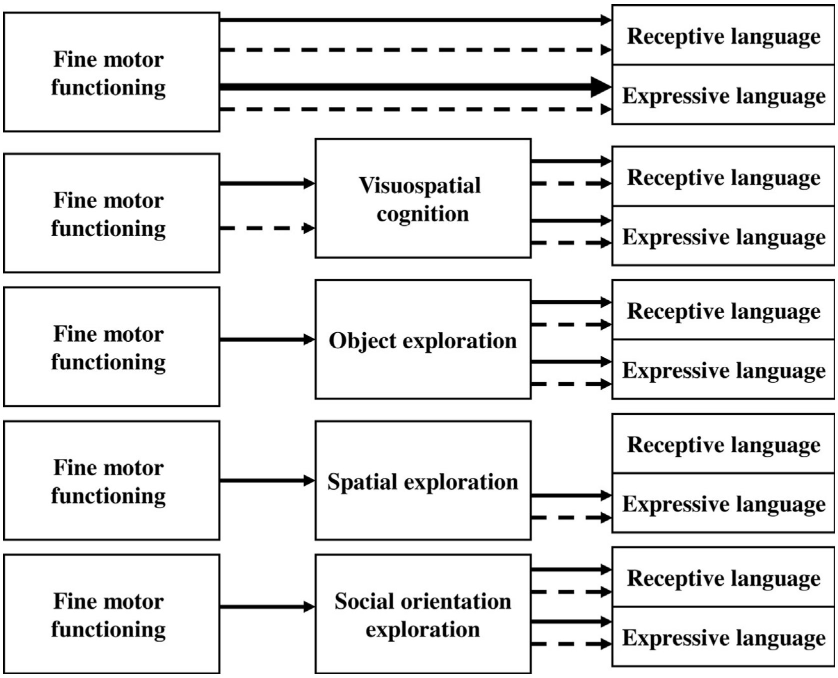

Fig. 1. Diagram of the relationship between fine motor functioning T1 and language T2 per group. *Note*: ASD group is indicated by ——▶, DD group is indicated by – – ▶. Some relationships were only found in the ASD group. The thicker arrow represents a stronger effect for that specific group.

Thereby, this study responds to the suggestions of other researchers to clarify the relationship of motor impairments with social and communication difficulties in ASD (Provost et al., 2007).

The current findings are in line with the embodied cognition theory, which suggests that cognition emerges from the bodily interactions of an agent with the environment (Smith & Gasser, 2005). Fine motor functioning may be indirectly related to language development because fine motor abilities facilitate the interaction with both the physical and social environment and improves visuospatial cognition which in turn stimulates language development. It should however be noted that fine motor functioning may also be directly related to language development, for instance because oral-motor skills are required for expressive language development (Gernsbacher et al., 2008).

In the current study, the fine motor skills of children with ASD were positively related to object and spatial exploration. This is consistent with the idea that motor skills constrain and guide exploratory behavior (Gibson, 1988; Gibson & Pick, 2000). Fine motor skills are necessary to act upon the environment, such as manipulating objects. The finding that fine motor skills are positively related to social orientation during exploration is also in accordance with other studies. Manual-motor skills are related to measures of social communication, such as nonverbal requesting, initiating joint attention, and responding to joint attention (Mundy, Kasari, Sigman, & Ruskin, 1995). It should be taken into account however that motor skills may not be the only possible predictors of exploratory behavior in ASD. A fragmented and detailed style of visual processing is often demonstrated in ASD (Brosnan, Scott, Fox, & Pye, 2004; Jolliffe & Baron-Cohen, 1997; Mottron, Burack, Iarocci, Belleville, & Enns, 2003; Mottron, Dawson, Souliéres, Hubert, & Burack, 2006; Pellicano, Gibson, Mayberry, Durkin, & Badcock, 2005; Schlooz et al., 2006) and this could well contribute to different exploratory behavior, such as atypical visual exploratory behavior (Mottron et al., 2007).

The finding that exploration is related to language development is consistent with other studies that demonstrated that sensorimotor experience is related to language and communication skills in preschool children with ASD (Poon, Watson, Baranek, & Poe, 2012; Toth, Munson, Meltzoff, & Dawson, 2006) and typically developing children (Antonucci & Alt, 2011; Iverson, 2010; Lifter & Bloom, 1989; Smith, 2013; Smith & Gasser, 2005; Wellsby & Pexman, 2014). The relationship between object/spatial exploration and language outcomes that was found in the current study can be explained by the fact that exploration facilitates an awareness of the physical environment, such as object perception, that is important for language. The finding that the social orientation during exploration is related to language development is in accordance with other studies. Joint attention is a predictor of the language development of children with ASD (Mundy, Sullivan, & Mastergeorge, 2009). The social orientation during exploration measure in the current study may be considered as a measure of the amount of joint attention initiated by the child during exploration. However, this relationship might also be indirect via social interaction. Exploration elicits social interaction behaviors of parents (Bornstein & Tamis-LeMonda, 1990; Clearfield et al., 2008) and social interaction stimulates language development.

In addition to the exploration measures, visuospatial cognition was also a mediator between fine motor functioning and language outcomes in both groups. Children with better fine motor skills might be more able to perform actions related to visuospatial cognition (e.g. sorting objects in space, putting objects in, on, or under each other). In accordance with evidence that visuospatial cognition is necessary to understand language (e.g. Humphries et al., 2004) the impaired visuospatial cognition of children with ASD may have influenced their language development.

By including a group with other developmental delays/disorders this study provided information as to whether the relationships between domains are specific to ASD. While most relationships were present in both groups, some relationships were only present in the ASD group. This is consistent with other studies that also found stronger relationships between abilities in different developmental domains in children with ASD compared to typically developing children and children with other developmental disorders (Dyck, Pieck, Hay, Smith, & Hallmayer, 2006; Liss et al., 2001).

The present study has several limitations that are important to mention. First of all, it is important to note that an unmeasured third variable may be responsible for the relationships found in the present study. Secondly, shared method variance by the measures of the MSEL may have overestimated relationships. However, in the MSEL each domain is assessed with a totally different set of tasks specifically focused on that area of functioning, the visuospatial cognition task for instance requires minimal motor responses. Moreover, exploration was not measured with the MSEL and measurements were longitudinal with at least 20 months between measurements. This increases confidence that the effect of shared method variance was minimal. The main shortcoming of this study is that no typically developing control group was included. Another limitation is that we can only draw conclusions regarding fine motor functioning, because gross motor data were not available for these children. Previous studies with typically developing children have demonstrated that gross motor functioning is also related to social and cognitive development (e.g. Campos et al., 2000; Smith & Gasser, 2005; Wijnroks & Van Veldhoven, 2003). However, by including the spatial exploration measure the effect of gross motor functioning may be taken into account since this measure was defined as moving through space, which requires gross motor skills.

In order to understand typical and atypical developmental trajectories it is important to assess how strengths or weaknesses in one domain may be affecting performance in other domains, which requires longitudinal research. The current study emphasizes the need for researchers and clinicians to consider cognition in general, and language specifically, as emergent from multiple interacting systems.

Acknowledgements

This study was supported by NWO-MW Chronic Disease Program grants 940-38-014 and 940-38-045; the NWO-MW grant 904-57-114; the Preventiefonds-ZonMw grant 28-3000-2; a grant from the Dutch Ministry of Health, Welfare and Culture and by grants from the Cure Autism Now and the Korczak foundation.

We wish to thank Herman van Engeland, Sophie Swinkels and Fabienne Naber for their contribution to the SOSO project. Also, we would like to thank Cindy van de Moosdijk for her contribution to this manuscript.

References

Akshoomoff, N. (2006). Use of the Mullen Scales of Early Learning for the assessment of young children with autism spectrum disorders. *Child Neuropsychology, 12*, 269–277.

Altman, D. G. (1991). *Practical statistics for medical research*. London: Chapman and Hall.

American Psychiatric Association (2000). *Diagnostic and statistical manual of mental disorders* (4th ed.). Washington, DC: American Psychiatric Association.

Antonucci, S. M., & Alt, M. (2011). A lifespan perspective on semantic processing of concrete concepts: does a sensory/motor model have the potential to bridge the gap. *Cognitive, Affective, & Behavioral Neuroscience, 11*, 551–572.

Baranek, G. T. (1999). Autism during infancy: A retrospective video analysis of sensory-motor and social behavior at 9–12 months of age. *Journal of Autism and Developmental Disorders, 29*, 213–224.

Baron-Cohen, S., Leslie, A. M., & Frith, U. (1985). Does the autistic child have a 'theory of mind'? *Cognition, 21*, 37–46.

Bavin, E. L., Wilson, P. H., Maruff, P., & Sleeman, F. (2005). Spatio-visual memory of children with specific language impairment: Evidence for generalized processing problems. *International Journal of Language and Communication Disorders, 40*, 319–332.

Bertone, A., Mottron, L., Jelenic, P., & Faubert, J. (2005). Enhanced and diminished visuo-spatial information processing in autism depends on stimulus complexity. *Brain, 128*, 2430–2441.

Bhat, A. N., Landa, R. J., & Cole, J. C. (2011). Current perspectives on motor functioning in infants, children and adults with autism spectrum disorders. *Physical Therapy, 91*, 1116–1129.

Bornstein, M. H., & Tamis-LeMonda, C. S. (1990). Activities and interactions of mothers and their firstborn infants in the first six months of life: Covariation, stability, continuity, correspondence, and prediction. *Child Development, 61*, 1206–1217.

Bourgeois, K. S., Khawar, A. W., Neal, S. A., & Lockman, J. J. (2005). Infant manual exploration of objects, surfaces, and their interactions. *Infancy, 8*, 233–252.

Brosnan, M. J., Scott, F. J., Fox, S., & Pye, J. (2004). Gestalt processing in autism: Failure to process perceptual relationships and the implications for contextual understanding. *Journal of Child Psychology and Psychiatry, 4*, 54–59.

Browne, M. W., & Cudeck, R. (1993). Alternative ways of assessing model fit. In K. Bollen & J. S. Long (Eds.), *Testing structural equation models* (pp. 136–162). Beverly Hills, CA: Sage.

Bruckner, C. T., & Yoder, P. (2007). Restricted object use in young children with autism: Definition and construct validity. *Autism, 11*, 161–171.

Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., & Witherington, D. (2000). Travel broadens the mind. *Infancy, 1*, 149–219.

Choi, S. (2000). Caregiver input in English and Korean: Use of nouns and verbs in bookreading and toy-play contexts. *Journal of Child Language, 27*, 69–96.

Clearfield, M. W. (2004). The role of crawling and walking experience in infant spatial memory. *Journal of Experimental Child Psychology, 89*, 214–241.

Clearfield, M. W. (2011). Learning to walk changes infants' social interactions. *Infant Behavior and Development, 34*, 15–25.

Clearfield, M. W., Osborne, C. N., & Mullen, M. (2008). Learning by looking: Infants' social looking behavior across the transition from crawling to walking. *Journal of Experimental Child Psychology, 100*, 297–307.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.

Dietz, C., Swinkels, S. H. N., Van Daalen, E., Van Engeland, H., & Buitelaar, J. K. (2006). Screening for autistic spectrum disorder in children aged 14 to 15 months II: Population screening with the Early Screening of Autistic Traits Questionnaire (ESAT). Design and general findings. *Journal of Autism and Developmental Disorders, 36*, 713–722.

Dyck, M. J., Pieck, J. P., Hay, D., Smith, L., & Hallmayer, J. (2006). Are abilities abnormally interdependent in children with autism. *Journal of Clinical Child and Adolescent Psychology, 35*, 22–33.

Edgin, J. O., & Pennington, B. F. (2005). Spatial cognition in autism spectrum disorders: Superior, impaired of just intact? *Journal of Autism and Developmental Disorders, 35*, 729–745.

Eigsti, I., Marchena, A., Schuh, J., & Kelley, E. (2011). Language acquisition in autism spectrum disorders: A developmental review. *Research in Autism Spectrum Disorders, 5*, 681–691.

Fischer, M. H., & Zwaan, R. A. (2008). Embodied language: A review of the role of the motor system in language comprehension. *The Quarterly Journal of Experimental Psychology, 61*, 825–850.

Fournier, K. A., Hass, C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2010). Motor coordination in autism spectrum disorders: A synthesis and meta-analysis. *Journal of Autism and Developmental Disorders, 40*, 1227–1240.

Gernsbacher, M. A., Sauer, E. A., Geye, H. M., Schweigert, E. K., & Goldsmith, H. H. (2008). Infant and toddler oral and manual motor skills predict later speech fluency in autism. *Journal of Child Psychology and Psychiatry, 49*, 43–50.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology, 39*, 1–42.

Gibson, E. J., & Pick, A. D. (2000). *An ecological approach to perceptual learning and development*. Oxford: Oxford University Press.

Glenberg, A., & Kaschak, M. (2002). Grounding language in action. *Psychonomic Bulletin & Review, 9*, 558–565.

Harman, K. L., Humphrey, G. K., & Goodale, M. A. (1999). Active manual control of object views facilitates visual recognition. *Current Biology, 22*, 1315–1318.

Hick, R., Botting, N., & Conti-Ramsden, G. (2005). Cognitive abilities in children with specific language impairment: Consideration of visuo-spatial skills. *International Journal of Language and Communication Disorders, 40*, 137–149.

Hill, E. L. (2001). Non-specific nature of specific language impairment: A review of the literature with regard to concomitant motor impairments. *International Journal of Language & Communication Disorders, 36*, 149–171.

Hockema, S. A., & Smith, L. B. (2009). Learning your language, outside-in and inside-out. *Linguistics, 47*, 453–479.

Howlin, P. (2003). Outcome in high-functioning adults with autism with and without language delays: Implications for the differentiation between autism and asperger syndrome. *Journal of Autism and Developmental Disorders, 33*, 3–13.

Humphries, T., Cardy, J. O., Worling, D. E., & Peets, K. (2004). Narrative comprehension and retelling abilities of children with nonverbal learning disabilities. *Brain and Cognition, 56*, 77–88.

Iverson, J. M. (2010). Developing language in a developing body: The relationship between motor development and language development. *Journal of Child Language, 37*, 229–261.

Iverson, J. M., & Thelen, E. (1999). Hand, mouth & brain: The dynamic emergence of speech and gesture. *Journal of Consciousness Studies, 6*, 19–40 Retrieved from http://cspeech.ucd.ie/~fred/docs/IversonThelen.pdf

Jansen-Osmann, P., Wiedenbauer, G., & Heil, M. (2008). Spatial cognition and motor development: A study of children with spina bifida. *Perceptual and Motor Skills, 106*, 436–446 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/18556900

Jolliffe, T., & Baron-Cohen, S. (1997). Are people with autism and asperger syndrome faster than normal on the embedded figures test? *Journal of Child Psychology and Psychiatry, 38*, 527–534.

Jones, S. S., & Smith, L. B. (2005). Object name learning and object perception: A deficit in late talkers. *Journal of Child Language, 32*, 223–240.

Kamhi, A. G., Catts, H. W., Mauer, D., Apel, K., & Gentry, B. F. (1988). Phonological and spatial processing abilities in language- and reading-impaired children. *Journal of Speech and Hearing Disorders, 53*, 316–327 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/3398484

Karmiloff, K., & Karmiloff-Smith, A. (2001). *Pathways to language: From fetus to adolescent*. Cambridge, MA: Harvard University Press.

Kjelgaard, M. M., & Tager-Flusberg, H. (2001). An investigation of language impairment in autism: Implications for genetic subgroups. *Language and Cognitive Processes, 16*, 287–308.

Kline, R. B. (1998). *Principles and practices of structural equation modeling*. New York: Guilford.

Koterba, E., Leezenbaum, N. B., & Iverson, J. M. (2012). Object exploration at 6 and 9 months in infants with and without for autism. *Autism, 18*, 97–105.

Küntay, A. C., & Özyürek, A. (2006). Learning to use demonstratives in conversation: What do language specific strategies in Turkish reveal? *Journal of Child Language, 33*, 303–320.

Kuschner, E. S., Bennetto, L., & Yost, K. (2007). Patterns of nonverbal cognitive functioning in young children with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 37*, 795–807.

Landa, R., & Garret-Mayer, E. (2006). Development in infants with autism spectrum disorders: A prospective study. *Journal of Child Psychology and Psychiatry, 47*, 629–638.

LeBarton, E. S., & Iverson, J. M. (2013). Fine motor skills predicts expressive language in infant siblings of children with autism. *Developmental Science, 16*, 815–827.

Lee, P. (1993). The development of early language and object knowledge in young children with mental handicap. *Early Child Development and Care, 95*, 85–103.

Lifter, K., & Bloom, L. (1989). Object knowledge and the emergence of language. *Infant Behavior and Development, 12*, 395–423.

Liss, M., Harel, B., Fein, D., Allen, D., Dunn, M., Feinstein, C., et al. (2001). Predictors and correlates of adaptive functioning in children with developmental disorders. *Journal of Autism and Developmental Disorders, 31*, 219–230.

Liu, C. H., Ward, J., & Markall, H. (2007). The role of active exploration of 3D face stimuli on recognition memory of facial information. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 895–904.

Lloyd, M., MacDonald, M., & Lord, C. (2013). Motor skills of toddlers with autism spectrum disorders. *Autism, 17*, 133–146.

López, B. (2013). Beyond modularization: The need of socio-neuro constructionist model of autism. *Journal of Autism and Developmental Disorders*.

Lord, C., Risi, S., Lambrecht, L., Cook, E. H., Jr., Leventhal, B. L., DiLavore, P. C., et al. (2000). The Autism Diagnostic Observation Schedule – Generic: A standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders, 30*, 205–223.

Lord, C., Rutter, M., Goode, S., Heemsbergen, J., Jordan, H., Mawhood, L., et al. (1989). Autism diagnostic observation schedule: A standardized observation of communicative and social behavior. *Journal of Autism and Developmental Disorders, 19*(2), 185–212.

Lord, C., Rutter, M., & Le Couteur, A. (1994). Autism Diagnostic Interview-Revised: A revised version of a diagnostic interview for caregivers of individuals with possible pervasive developmental disorders. *Journal of Autism and Developmental Disorders, 24*, 659–685.

Marton, K. (2008). Visuo-spatial processing and executive functions in children with specific language impairment. *International Journal of Language and Communication Disorders, 43*, 181–200.

Masten, A. S., & Cicchetti, A. D. (2010). Developmental cascades. *Development and Psychopathology, 22*, 491–495.

McDonough, L., Choi, S., & Mandler, J. M. (2003). Understanding spatial relations: Flexible infants, lexical adults. *Cognitive Psychology, 46*, 229–259.

Meijer, F., & Van der Lubbe, R. H. J. (2011). Active exploration improves perceptual sensitivity for virtual 3D objects in visual recognition tasks. *Vision Research, 51*, 2431–2439.

Mitchell, P., & Ropar, D. (2004). Visuo-spatial abilities in autism: A review. *Infant and Child Development, 13*, 185–198.

Mottron, L., Burack, J., Iarocci, G., Belleville, G. S., & Enns, J. (2003). Locally oriented perception with intact global processing among adolescents with high functioning autism: Evidence from multiple paradigms. *Journal of Child Psychology and Psychiatry, 44*, 906–913.

Mottron, L., Dawson, M., Souliéres, I., Hubert, B., & Burack, J. (2006). Enhanced perceptual functioning in autism: An update and eight principles of autistic perception. *Journal of Autism and Developmental Disorders, 38*, 27–43.

Mottron, L., Mineau, S., Martel, G., Saintonge, C., Berthiaume, C., Dawson, M., et al. (2007). Lateral glances toward moving stimuli among toddlers with autism: Early evidence of locally-oriented perception? *Development and Psychopathology, 19*, 23–36.

Mullen, E. M. (1995). *Mullen Scales of Early Learning* (AGS ed.). Circle Pines, MN: American Guidance Service.

Mundy, P., Kasari, C., Sigman, M., & Ruskin, E. (1995). Nonverbal communication and early language acquisition in children with Down syndrome and in normally developing children. *Journal of Speech and Hearing Research, 38*, 157–167 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/7537345

Mundy, P., Sullivan, L., & Mastergeorge, A. M. (2009). A parallel and distributed-processing model of joint attention, social cognition and autism. *Autism Research, 2*, 2–21.

Needham, A. (2000). Improvements in object exploration skills may facilitate the development of object segregation in early infancy. *Journal of Cognition and Development, 1*, 131–156.

O'Riordan, M. A., Plaisted, K. C., Driver, J., & Baron-Cohen, S. (2001). Superior visual search in autism. *Journal of Experimental Psychology: Human Perception and Performance, 27*, 719–730.

Ozonoff, S., Macari, S., Young, G. S., Goldring, S., Thompson, M., & Rogers, S. J. (2008). Atypical object exploration at 12 months of age is associated with autism in a prospective sample. *Autism, 12*, 457–472.

Ozonoff, S., Pennington, B. F., & Rogers, S. J. (1991). Executive function deficits in highfunctioning autistic individuals: Relationship to theory of mind. *Journal of Child Psychology and Psychiatry, 32*, 1081–1105.

Paterson, S. J., Brown, J. H., Gsödl, M. K., Johnson, M. H., & Karmiloff-Smith, A. (1999). Cognitive modularity and genetic disorders. *Science, 286*, 2355–2358.

Pellicano, E., Gibson, L., Mayberry, M., Durkin, K., & Badcock, D. R. (2005). Abnormal global processing along the dorsal visual pathway in autism: A possible mechanism for weak central coherence. *Neuropsychologica, 43*, 1044–1053.

Pereira, A. F., James, K. H., Jones, S. S., & Smith, L. B. (2008). Active object exploration in toddlers and its role in visual object recognition. *Proceedings of the 30th annual meeting of the cognitive science society*.

Pereira, A. F., & Smith, L. B. (2009). Developmental changes in visual object recognition between 18 and 24 months of age. *Developmental Science, 12*, 67–80.

Perone, S., Madole, K. L., Ross-Sheehy, S., Carey, M., & Oakes, L. M. (2008). The relation between infants' activity with objects and attention to object appearance. *Developmental Psychology, 44*, 1242–1248.

Pierce, K., & Courchesne, E. (2001). Evidence for a cerebellar role in reduced exploration and stereotyped behavior in autism. *Biological Psychiatry, 49*, 655–664.

Poon, K. K., Watson, L. R., Baranek, G. T., & Poe, M. D. (2012). To what extent do joint attention, imitation, and object play behaviors in infancy predict later communication and intellectual functioning in ASD? *Journal of Autism and Developmental Disorders, 42*, 1064–1074.

Preacher, K. J., & Hayes, A. F. (2004). SPSS and SAS procedures for estimating indirect effects in simple mediation models. *Behaviour Research Methods, Instruments and Computers, 36*, 717–731 Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/15641418

Preacher, K. J., Rucker, D. D., & Hayes, A. F. (2007). Addressing moderated mediation hypotheses: Theory, methods and prescriptions. *Multivariate Behavioral Research, 42*, 185–227.

Provost, B., Lopez, B. R., & Heimerl, S. (2007). A comparison of motor delays in young children: Autism spectrum disorder, developmental delay, and developmental concerns. *Journal of Autism and Developmental Disorders, 37*, 321–328.

Pulvermüller, F. (2005). Brain mechanisms linking language and action. *Nature Reviews Neuroscience, 6*, 576–582.

Pulvermüller, F., & Fadiga, L. (2010). Active perception: Sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience, 11*, 351–360.

Richardson, D. C., Spivey, M. J., Barsalou, L. W., & McRae, K. (2003). Spatial representations activated during real-time comprehension of verbs. *Cognitive Science, 27*, 767–780.

Rochat, P. (1989). Object manipulation and exploration in 2- to 5-month-old infants. *Developmental Psychology, 25*, 871–884.

Ruff, H. A. (1984). Infants' manipulative exploration of objects: Effects of age and object characteristics. *Developmental Psychology, 20*, 9–20.

Ruff, H. A., McCarton, C., Kurzberg, D., & Vaughan, H. G. (1984). Preterm infants' manipulative exploration of objects. *Child Development, 55*, 1166–1173 Retrieved from http://www.jstor.org/stable/1129985

Samuelson, L. K., & Smith, L. B. (1999). Early noun vocabularies: Do ontology, category structure and syntax correspond? *Cognition, 73*, 1–33.

Sasaoka, T., Asakura, N., & Kawahara, T. (2010). Effect of active exploration of 3-D object views on the view-matching process in object recognition. *Perception, 39*, 289–308.

Schlooz, W. A. J., Hulstijn, W., Van den Broek, P. J. A., Van der Pijl, A. C. A. M., Gabreels, F., Van der Graag, R. J., et al. (2006). Fragmented visuospatial processing in children with pervasive developmental disorder. *Journal of Autism and Developmental Disorders, 36*, 1025–1037.

Scofield, J., Hernandez-Reif, M., & Keith, A. B. (2009). Preschool children's multimodal word learning. *Journal of Cognition and Development, 10*, 306–333.

Smith, L. B. (2003). Learning to recognize objects. *Psychological Science, 14*, 244–250.

Smith, L. B. (2005a). Cognition as a dynamic system: Principles from embodiment. *Developmental Review, 25*, 278–298.

Smith, L. B. (2005b). Action alters shape categories. *Cognitive Science, 29*, 665–679.

Smith, L. B. (2013). It's all connected: Pathways in visual object recognition and early noun learning. *American Psychologist, 68*, 618–629.

Smith, L. B., & Gasser, M. (2005). The development of embodied cognition: Six lessons from babies. *Artificial Life, 11*, 13–30.

Son, J. Y., Smith, L. B., & Goldstone, R. L. (2008). Simplicity and generalization: Short-cutting abstraction in children's object categorizations. *Cognition, 108*, 626–638.

Soska, K. C., Adolph, K. E., & Johnson, S. P. (2010). Systems in development: Motor skill acquisition facilitates three-dimensional object completion. *Developmental Psychology, 46*, 129–138.

Stone, W. L., & Yoder, P. J. (2001). Predicting spoken language in children with autism spectrum disorders. *Autism, 5*, 341–361.

Swinkels, S. H. N., Dietz, C., Van Daalen, E., Kerkhof, I. H. G. M., Van Engeland, H., & Buitelaar, J. K. (2006). Screening for autistic spectrum disorder in children aged 14 to 15 months: The development of the Early Screening for Autistic Traits questionnaire (ESAT). *Journal of Autism and Developmental Disorders, 36*, 723–732.

Thelen, E. (2000a). Motor development as foundation and future of developmental psychology. *International Journal of Behavioral Development, 24*, 385–397.

Thelen, E. (2000b). Grounded in the world: Developmental origins of the embodied mind. *Infancy, 1*, 3–28.

Toth, K., Munson, J., Meltzoff, A. N., & Dawson, G. (2006). Early predictors of communication development in young children with autism spectrum disorder: Joint attention, imitation, and toy play. *Journal of Autism and Developmental Disorders, 36*, 993–1005.

Vlamings, P. H. J. M., Jonkman, L. M., van Daalen, E., van der Gaag, R. J., & Kemner, C. (2010). Basic abnormalities in visual information processing affect face processing at an early age in autism spectrum disorder. *Biological Psychiatry, 68*, 1107–1113.

Wellsby, M., & Pexman, P. M. (2014). Developing embodied cognition: Insights from children's concepts and language processing. *Frontiers in Psychology, 5*, 506.

Wetherby, A. M., Woods, J., Allen, L., Cleary, J., Dickinson, H., & Lord, C. (2004). Early indicators of autism spectrum disorders in the second year of life. *Journal of Autism and Developmental Disorders, 34*, 473–493.

Wijnroks, L., & Van Veldhoven, N. (2003). Individual differences in postural control and cognitive development in preterm infants. *Infant Behavior & Development, 26*, 14–26.

Williams, E., Costall, A., & Reddy, V. (1999). Children with autism experience problems with both objects and people. *Journal of Autism and Developmental Disorders, 29*, 367–378.

Yee, E., Chrysikou, E. G., Hoffman, E., & Thompson-Schill, S. L. (2013). Manual experience shapes object representations. *Psychological Science, 24*, 909–919.

Zwaigenbaum, L., Bryson, S., Rogers, T., Roberts, W., Brian, J., & Szatmari, P. (2005). Behavioral manifestations of autism in the first year of life. *International Journal of Developmental Neuroscience, 23*, 143–152.