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Predicting the rate of language development from early motor skills in at-risk infants who develop autism spectrum disorder

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ABSTRACT

The aim of the current paper was to use data from a prospective study to assess the impact of early motor skills on the rate of language development in infants with an older sibling with autism spectrum disorder (ASD), who are at increased risk of developing ASD themselves. Infants were tested prospectively at four points (7, 14, 24 and 36 months), and were assessed for ASD at the last visit. Latent growth curve analysis was used to model rate of language development using the Vineland Adaptive Behavior Scales between 7–36 months in infants at high and low familial risk for ASD. Motor scores from the Mullen Scales of Early Learning at 7 months were used as predictors of language growth. Gross Motor scores predicted the subsequent rate of expressive, but not receptive, language development in at-risk siblings who were later diagnosed with ASD. Although the pattern was similar for fine motor skills, the relationship did not reach significance. It seems that early motor delay impacts the rate of development of *expressive* language, and this may be of particular importance to infants at increased risk of developing ASD.

1. Introduction

The achievement of gross motor milestones, such as crawling and walking, is widely understood to be significant in a child's life. However, the relationship between motor development and other key skills is not always recognised (Leonard & Hill, 2014). Motor development has often been viewed as a separate system to those traditionally studied by psychologists (Rosenbaum, 2005), but more recently there has been increasing interest in its effect on cognition and behaviour. The conceptualisation of motor development as part of a complex dynamic system (Thelen & Smith, 1994) has encouraged greater investigation of the constraints placed on the developing infant in terms of emerging motor skills (i.e., object manipulation, postural changes and locomotion), and the impact that relatively small changes in this component can have on other parts of the system. This approach is of particular interest in neurodevelopmental disorders, including autism

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spectrum disorder (ASD), in which it is likely that early disruptions in specific aspects of the system have cascading effects on a number of different areas of development (Bishop, 1997; Karmiloff-Smith, 1998).

The focus of the current study is on the relationship between early motor skills and the development of language in ASD. ASD is diagnosed on the basis of atypical use of language and nonverbal communication in social contexts, which interferes with typical social functioning, as well as repetitive and restricted patterns of behaviour and interests (American Psychiatric Association, 2013). An increasing number of studies have also identified motor difficulties in individuals with ASD (see Bhat, Landa, & Galloway, 2011, for a review). However, few have considered the relationship between motor and language development in those with a diagnosis. In studies of typically developing infants and children, research has suggested that increasingly sophisticated locomotion produces more social referencing and joint attention, as well as more directed gestures and social bids towards others (Campos et al., 2000; Clearfield, Osborne, & Mullen, 2008; Clearfield, 2011; Karasik, Tamis-LeMonda, & Adolph, 2011; Tamis-LeMonda et al., 2008). Other studies have reported that the achievement of key motor milestones, such as unsupported sitting and walking, is related to better expressive vocabulary (Oudgenoeg-Paz, Volman, & Leseman, 2012; Walle & Campos, 2014), as is increasingly complex object manipulation (Lifter & Bloom, 1989). As children's language level increases with age, significant correlations with gross and fine motor skills continue to be reported (Alcock & Krawczyk, 2010; Cheng, Chen, Tsai, Chen, & Cherng, 2009; Wang, Lekhal, Aarø, & Schjølberg, 2012).

Despite this apparent coupling of language and motor development in early life and the atypicalities reported in language and motor skills in ASD, relatively few studies have considered the relationships between these two developing systems in the disorder. This may be due to the fact that ASD is generally diagnosed after the age of 2 (Charman & Baird, 2002), meaning that the early motor milestones have already been achieved and must therefore be reported retrospectively by parents (e.g., Gernsbacher, Sauer, Geye, Schweigert, & Goldsmith, 2008; Kim, 2008). An alternative approach to investigating the relationship between motor and language skills in ASD is by conducting prospective studies with the younger siblings of children with a diagnosis, who are at increased risk of developing ASD themselves (Constantino, Zhang, Frazier, Abbacchi, & Law, 2010; Ozonoff et al., 2011). This approach allows researchers to compare at-risk infants to infants with no family history of ASD (hereafter, "low-risk"), and to attempt to identify early markers of atypical development in those infants who go on to develop ASD (see Elsabbagh & Johnson, 2010). A number of prospective studies have identified early motor differences in at-risk infants compared to low-risk infants (e.g., Landa & Garrett-Mayer, 2006; LeBarton & Iverson, 2013; Leonard, Elsabbagh, & Hill, the BASIS team, 2013; Toth, Dawson, Meltzoff, Greenson, & Fein, 2007; see Bhat et al., 2011, for a review). Although few have directly assessed the relationship between early motor skills and language development, a study by Bhat, Galloway, and Landa (2012) suggested an association between motor delay at 3 months and communication delay at 18 months in at-risk infants. Furthermore, LeBarton and Iverson (2013) reported that fine motor skills (from a composite score of these skills between 12 and 24 months) significantly predicted expressive language outcomes in at-risk infants at 36 months. Given the range of motor difficulties and atypicalities now reported in ASD, as well as the studies that have been conducted in this area that suggest a link between motor and language skills in at-risk infants, a more detailed analysis of the relationship between early motor skills and language development is required.

The current paper addresses this issue, using statistical modelling to assess the relationship between developing motor skills and the rate of language development in a prospective study of infants at risk of developing ASD. This is the first study, to our knowledge, that presents an analysis of the *rate* of language development in relation to motor skill in a prospective design. This is an important distinction, as it allows an analysis of the impact of motor ability on the *development* of language, not merely the language outcome. Understanding the way in which a key skill develops over time in neurodevelopmental disorders is vital, as individuals may reach a particular outcome through a number of atypical developmental trajectories, and these alternative trajectories could provide vital insight into the language and communication difficulties in ASD (e.g., Karmiloff-Smith, 1998, 2009). The data presented here were collected as part of a larger prospective study of at-risk and low-risk infants. Specifically, the current paper focuses on data extracted from the Vineland Adaptive Behavior Scales (VABS-II; Sparrow, Cicchetti, & Balla, 2005), which is a parent report measure of communication, daily living, socialisation and motor skills, and from the Mullen Scales of Early Learning (MSEL; Mullen, 1995), which is a standardised assessment of motor, language and cognitive abilities. Data were collected at 7, 14, 24, and 36 months for both measures, and the participants were assessed for ASD at 36 months. In the current analyses, motor skills from the MSEL at 7 months were used to predict the *rate* of expressive and receptive language development (assessed by the VABS-II between 7 and 36 months), which was modelled using latent growth curve analysis. The age of 7 months was the earliest time point available within the current dataset, and was also considered likely to provide some variability in the motor skills developed by different infants. Milestones such as sitting without support and crawling are achieved by some infants around this age, while others take much longer to reach this developmental stage (World Health Organization, 2006). The rate of language development was assessed using the VABS-II, as we expected parents to notice more fine-grained changes in their child's language production (expressive language) and understanding (receptive language) during this time period than might be seen through standardised assessment in an unfamiliar setting (as measured by MSEL). Moreover, this measure assesses a number of aspects of language and does not focus purely on vocabulary. Finally, correlations between the different scales on the same standardised assessment would be expected, and thus any relationships across different measures (MSEL vs. VABS-II) may provide more insight into the behaviour observed than using the MSEL for both motor and language skills.

Due to the important role of language in the social communication and interaction difficulties in ASD, and the potential significance of motor skills as an early indicator of language delay, the current paper focuses on those at-risk infants who were classified as having ASD at 36 months. These infants were compared to both the low-risk group and those at-risk infants who did not receive a diagnosis of ASD at 36 months. Based on previous research, it was expected that motor skills would significantly predict the rate of language development, although no specific prediction was made about whether this relationship would differ between groups. As this was the first analysis of its kind, it was not clear if gross and fine motor skills would be equally good predictors of language development, or indeed if the rate of development of receptive and expressive language would be equally affected by early motor skills. However, based on previous research, it was expected that gross motor skills at 7 months would predict expressive language rate in the typically developing group (Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014), and fine motor skills at 7 months would predict expressive language rate in the at-risk group (LeBarton & Iverson, 2013).

2. Method

2.1. Participants

Participants were families taking part in an ongoing longitudinal research programme, The British Autism Study of Infant Siblings (BASIS; www.basisnetwork.org), a UK collaborative network facilitating research with infants at-risk for autism. Fifty-four at-risk infants (22 males) were recruited from a database of volunteers on the basis that they had an older sibling (hereafter "proband": four = half-sibling) with a community diagnosis of ASD, which was confirmed by two expert clinicians using the Development and Wellbeing Assessment (DAWBA; Goodman, Ford, Richards, Gatward, & Meltzer, 2000) and the parent-report Social Communication Questionnaire (SCQ-Lifetime; Rutter, Bailey, & Lord, 2003). Fifty low-risk infants were recruited on the basis that they had at least one older-sibling (three = half-siblings), none of whom scored above the ASD cut-off on the SCQ (one score was missing). At the time of enrolment, none of the infants had been diagnosed with any medical or developmental condition. Further details of recruitment and sample characteristics are presented in Elsabbagh et al. (2013), and are provided in Appendix A.

The current study was interested in the differences in development in those at-risk infants who later achieved a diagnosis of ASD compared to those who did not, as well as compared to low-risk infants. All participants were assessed at 36 months using the Autism Diagnostic Observation Schedule – Generic (ADOS-G; Lord, Rutter, DiLavore, & Risi, 2000), and parents in the at-risk group completed the Autism Diagnostic Interview – Revised (ADI-R; Lord, Rutter, & LeCouteur, 1994), and consensus ICD-10 (World Health Organization, 1993). ASD diagnoses were achieved using all available information from all visits by experienced researchers. Based on these assessments, the at-risk group was split into two subgroups (see Table 1 for participant characteristics of each subgroup): 17 'ASD-sibs' who met ICD-10 criteria for ASD and scored above the cut-off on the ADOS-G or ADI-R, and 36 'NoASD-sibs' who did not meet ICD-10 criteria for ASD.

2.2. Materials and procedure

The MSEL (Mullen, 1995) is a standardised test suitable for testing receptive and expressive language, visual reception and gross and fine motor skills between the ages of 0 and 68 months. It was one assessment of a range of tasks conducted during testing visits at 7, 14, 24, and 36 months. The assessment was conducted in a quiet room with the infant sitting on the parent's lap or with the parent on the floor, depending on the scale and the item of the MSEL being completed at the time. For the current analyses, the Gross Motor, Fine Motor and Visual Reception scores from the first visit (age 7 months) were used. The Visual Reception Scale measures visual perceptual ability, using items such as visual tracking of different stimuli and the identification of an object, and was used in the current analyses as a proxy for general developmental differences (see Leonard et al., 2013). Skills such as sitting independently (Gross Motor), reaching and grasping objects (Fine Motor), and tracking objects in the visual field (Visual Reception) are scored as either "Present" or "Absent." Raw scores from the three scales are transformed into *T*-Scale scores, mean = 50 (SD = 10).

Table 1
Participant characteristics for the low-risk group and the at-risk subgroups with and without an ASD diagnosis at 36 months.

Visit	Group	*N* (males)	Age in months mean (SD)
7 months	Low-risk	48 (17)	7.42 (1.25)
	ASD-sibs	17 (11)	7.53 (1.23)
	NoASD-sibs	36 (10)	7.17 (1.16)
14 months	Low-risk	47 (16)	13.94 (1.34)
	ASD-sibs	17 (11)	13.94 (1.6)
	NoASD-sibs	35 (10)	13.51 (1.56)
24 months	Low-risk	47 (17)	23.87 (0.68)
	ASD-sibs	16 (10)	24.00 (0.97)
	NoASD-sibs	36 (10)	23.90 (1.24)
36 months	Low-risk	48 (17)	38.23 (3.05)
	ASD-sibs	17 (11)	37.76 (2.11)
	NoASD-sibs	36 (10)	37.61 (3.36)

The VABS-II (Sparrow et al., 2005) is a parent report measure suitable from birth to adulthood. The questionnaire was completed at home by parents and checked by a researcher before the following testing session, or the interview version of the questionnaire was administered by a researcher. For the current analyses, scores from the Expressive Language and Receptive Language Scales from all four age points were used. Parents/caregivers reported whether their child could produce particular vocalisations/words (expressive language) or understood specific verbal information (receptive language) on a scale of "Never", "Sometimes" or "Usually." "Don't Know" or "No Opportunity" responses were also possible.

2.3. Statistical analysis

Shown in Fig. 1, separate growth curve models (GCMs) for raw expressive and receptive language were estimated in Mplus computer program (Muthén & Muthén, 2011). In a latent GCM both the intercept and slope of the regression equation are specified as latent variables, which are random and can vary across individuals. The ability to quantify individual differences in developmental trajectories gives GCMs a substantial advantage over the techniques typically used by developmental psychology researchers (e.g., Curran & Hussong, 2003). In these models, time is parameterised and we took advantage of this to account for the variability in the age at which children were tested (e.g., while mean age at visit 1 was 7.35, infants ranged from 6 to 10 months) by setting the regression pathways to the chronological age of the child. The GCMs were estimated using the Mplus *t* scores option with analysis type = random, and allowing the slope and intercept to be correlated. While no absolute model fit statistics were available, the Bayesian information criterion (BIC) was 2783 for Expressive Language (EL) and 2254 for Receptive Language (RL). The 'slope' factor scores were then extracted and used as the dependent variable in multiple regression analyses in SPSS. For the current paper, both MSEL Fine Motor (FM) and Gross Motor (GM) *T*-scores were of interest as predictors of the rate of expressive and receptive language development.

3. Results

The means and standard deviations of *T*-scores for the three groups (low-risk group, ASD-sibs and NoASD-sibs subgroups) from the MSEL Motor Scales and Visual Reception Scale at the 7-month visit are presented in Table 2. The VABS-II Language raw scores from all four visits are provided in Table 3.

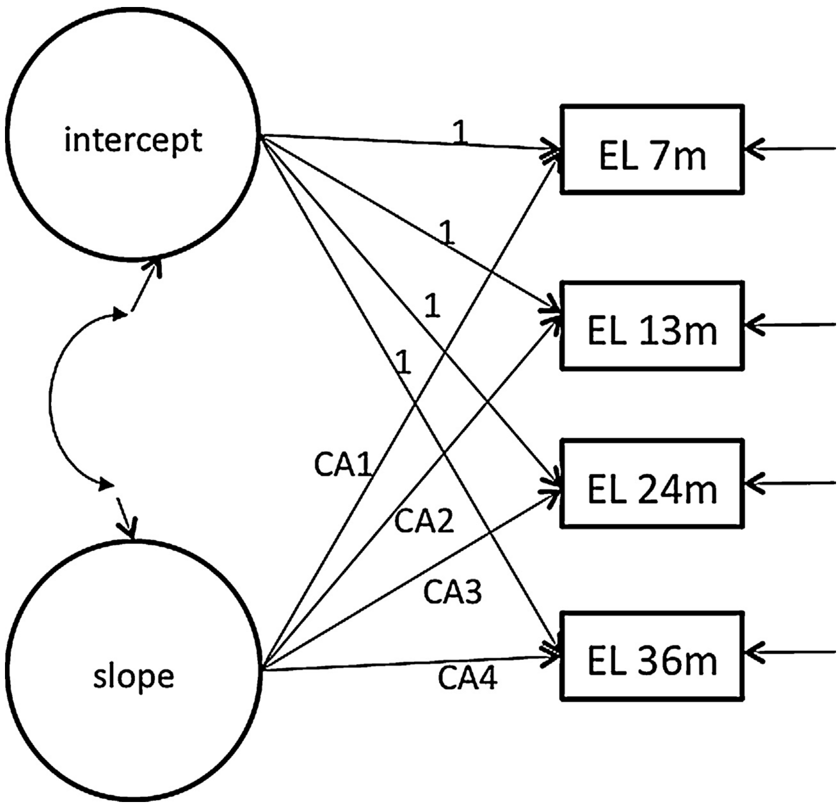

Fig. 1. Growth curve model for Vineland Adaptive Behavior Scales Expressive Language from 7–36 months, with 'slope' regression coefficients set at the child's chronological age.

Table 2
Mean *T*-scores (and standard deviations) of Gross Motor, Fine Motor and Visual Reception Scales of the Mullen Scales of Early Learning at the 7-month visit.

Scale	Low-risk	ASD-sibs	NoASD-sibs
Gross Motor	50.17 (8.98)	46.06 (12.58)	45.33 (8.84)
Fine Motor	57.79 (9.49)	49.81 (11.08)	53.67 (10.26)
Visual Reception	54.73 (8.63)	50.00 (11.49)	50.67 (7.89)

Table 3
Mean raw scores (and standard deviations) of Expressive Language and Receptive Language Scales of the Vineland Adaptive Behavior Scales-II at the 7-, 14-, 24- and 36-month visits.

Scales	Low-risk	ASD-sibs	NoASD-sibs
7 months			
Expressive Language	11.89 (2.50)	10.41 (4.11)	10.71 (3.22)
Receptive Language	8.23 (2.20)	6.82 (2.13)	6.80 (2.10)
14 months			
Expressive Language	21.37 (4.70)	17.12 (7.45)	19.76 (7.08)
Receptive Language	15.15 (4.46)	10.76 (4.47)	11.88 (4.30)
24 months			
Expressive Language	51.62 (14.55)	46.50 (16.88)	46.19 (11.72)
Receptive Language	26.28 (4.02)	21.50 (6.38)	24.08 (3.86)
36 months			
Expressive Language	81.70 (8.62)	63.65 (19.98)	73.44 (11.05)
Receptive Language	32.63 (3.67)	26.94 (7.02)	31.17 (4.00)

Table 4
Summary details of regressions predicting the rate of Expressive Language development. For each regression, MSEL motor scores (gross or fine motor, respectively) were entered as a predictor, along with MSEL Visual Reception scores. Two further dummy-coded variables were entered (D1: the comparison between ASD-sibs and the low-risk group; D2: the comparison between ASD-sibs and NoASD-sibs), and the interactions between these dummy-coded variables and MSEL motor scores were also specified (D1*GM and D2*GM).

	Expressive Language Rate β (S.E.)
Gross Motor model	
MSEL GM	0.015* (0.007)
MSEL VR	0.005 (0.004)
D1 (ASD-sibs vs. LR)	1.43* (0.43)
D2 (ASD-sibs vs. NoASD-sibs)	0.87** (0.44)
D1*GM	−0.022* (0.009)
D2*GM	−0.014 (0.009)
Fine Motor model	
MSEL FM	0.015 (0.008)
MSEL VR	0.006 (0.004)
D1 (ASD-sibs vs. LR)	1.37* (0.50)
D2 (ASD-sibs vs. NoASD-sibs)	1.25* (0.50)
D1*FM	−0.019* (0.009)
D2*FM	−0.020* (0.01)

Note: MSEL, Mullen Scales of Early Learning; FM, fine motor; GM, gross motor; VR, visual reception; LR, low risk.
* $p < 05$.
** $p = .05$.

3.1. Rate of expressive language development

A multiple linear regression model was run with rate of expressive language development (EL, as measured by the VABS) as the dependent variable, with the following predictor variables: MSEL GM and VR *T*-scores, dummy variables for ASD-sibs vs. low-risk (D1) and NoASD-sibs (D2), and the interaction terms D1*GM and D2*GM.

As shown in Table 4, the interaction between Gross Motor score and the ASD-sibs vs. low-risk comparison (D1*GM) was significant ($p = 0.014$). This indicates a significant difference in the relationship between gross motor skill and the rate of expressive language development for the ASD-sibs compared to the low-risk group. Testing the slope coefficient against ‘0’ within each of these groups indicates a significant positive relationship for the ASD group, $F(1, 93) = 4.51$, $p = 0.036$, but no relationship in the low-risk group, $F(1, 93) = 1.56$, $p = 0.22$ (see Fig. 2). The regression equation for ASD-sibs was $y = 0.89 + 0.015x + e_i$, suggesting that for each one point increase in Gross Motor *T*-score, there was a gain of 0.44 months (or ~13 days) in the rate of language development from 7 to 36 months (i.e., 0.015*29). The interaction between Gross Motor score and the ASD-sibs vs. NoASD-sibs comparison (D2*GM) was not significant ($\beta = -0.01$, S.E. = 0.009, $p = 0.15$), suggesting no significant difference in the relationship between Gross Motor score and the rate of expressive language growth between the two at-risk subgroups. A separate model which included as an additional predictor '7-month expressive language' yielded substantively similar results, indicating that the relationship between Gross Motor score and the rate of expressive language development was different in ASD-sibs and low-risk children even after accounting for expressive language at 7 months (see Appendix A for details).

A separate model was run with MSEL Fine Motor, rather than Gross Motor, score as a predictor of the slope of VABS EL development (see Table 4). Both the D1*FM interaction for ASD-sibs vs. low-risk children ($p = 0.046$) and the D2*FM interaction for ASD-sibs vs. NoASD-sibs ($p = 0.04$) were significant, indicating a significant difference in the relationships between Fine Motor skill and the rate of expressive language development in the ASD-sibs compared to the other groups. Despite these significant interactions, testing the slopes for ASD-sibs, low-risk and NoASD-sibs separately showed that while the slopes differed from one another, they were not significantly different from '0': $F(1, 93) = 3.48$, $p = 0.07$ (ASD-sibs); $F(1, 93) = 0.57$, $p = 0.45$ (low-risk); and $F(1, 93) = 0.7$, $p = 0.41$ (NoASD-sibs). However, this result was marginal for the ASD-sibs, and examination of Fig. 3 shows the pattern of results to be somewhat similar to those for Gross Motor scores. As with the Gross Motor data, a separate model was run which included '7-month expressive language' as an additional predictor. In this case, there was a trend for the ASD group to differ from the low-risk group once language was taken into account in the model (see Appendix A for more details).

3.2. Rate of receptive language development

No significant motor*outcome group interactions were found for rate of receptive language: D1(ASD-sibs vs. low-risk)*GM ($\beta = -0.003$, S.E. = 0.002, $p = 0.17$), and D2 (ASD-sibs vs. NoASD-sibs)*GM ($\beta = -0.001$, S.E. = 0.002, $p = 0.56$); D1*FM ($\beta = -0.003$, S.E. = 0.002, $p = 0.28$), and D2*FM ($\beta = -0.003$, S.E. = 0.002, $p = 0.25$; see Appendix A for further details).

4. Discussion

The current paper is the first to address the relationship between early motor skills and the *rate* of language development in at-risk infants who develop ASD compared to those who do not. Using a prospective design, the analyses presented here

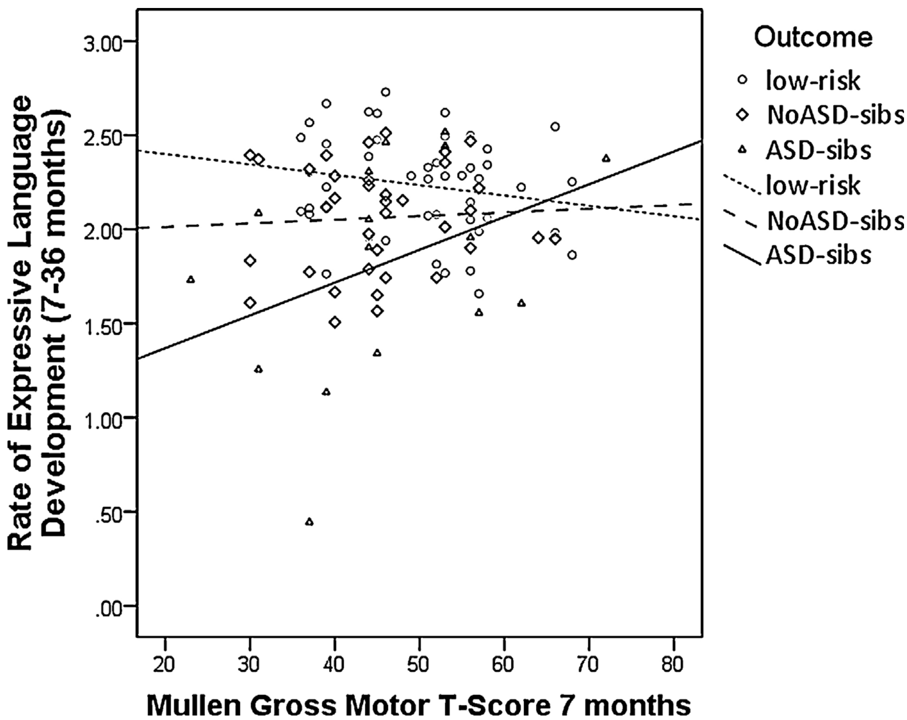

Fig. 2. Relationship between MSEL Gross Motor score and rate of VABS-II Expressive Language growth (from 7 to 36 months) for ASD, NoASD-sibs and low-risk groups. To aid interpretation, the graph shows the relationship without controlling for VR.

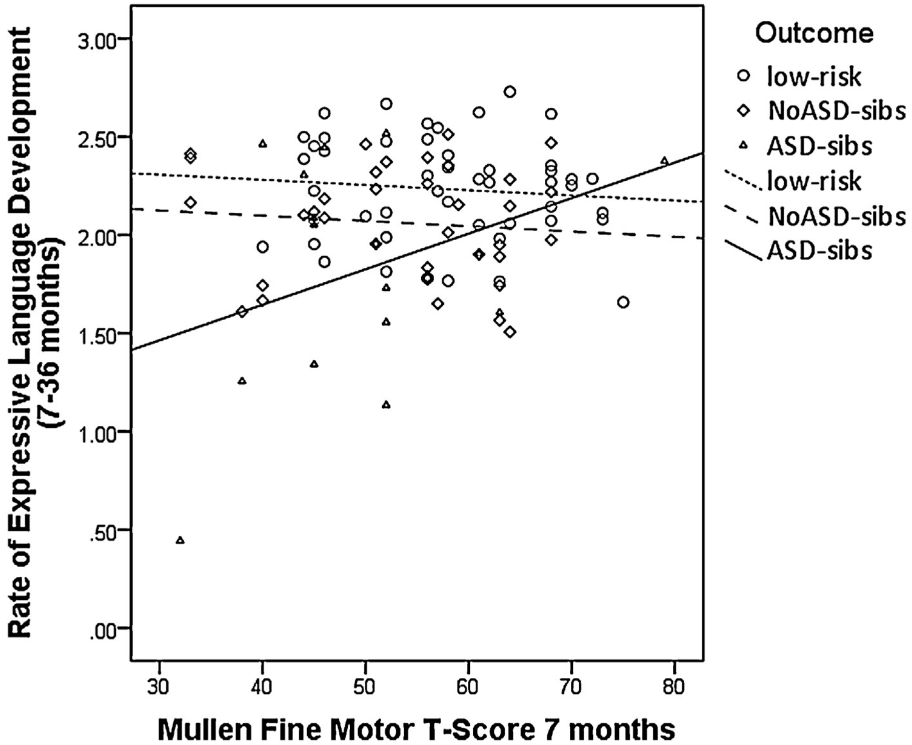

Fig. 3. Relationship between MSEL Fine Motor score and rate of VABS-II Expressive Language growth (from 7 to 36 months) for ASD-sibs, NoASD-sibs and low-risk groups. To aid interpretation, the graph shows the relationship without controlling for VR.

suggest that the rate of expressive language can be predicted by early motor skill, and that the relationship between motor and language development differs between infants who develop ASD and those who do not. These group differences were significant over and above any possible effect of different developmental levels between the groups (as assessed by the MSEL Visual Reception scores), and even after expressive language at 7 months was taken into account. No significant relationship was found between gross or fine motor skills and the rate of receptive language development in any group.

The current finding of a significant relationship between gross motor skills and expressive language in the ASD-sibs subgroup is in line with the results of Bhat et al. (2012), who reported that poorer early motor skills were associated with poorer communication outcomes at 18 months. However, while the relationships between fine motor skills and expressive language rate differed significantly between the ASD-sibs subgroup and both other groups, this relationship within each individual group did not reach significance (i.e., the regression slopes differed from each other, but did not differ significantly from zero). This is at odds with the analyses conducted by LeBarton and Iverson (2013), who reported a significant relationship between fine motor skills and expressive language in an at-risk group, and no significant differences between subgroups who developed ASD and those who did not. One difference between the current study and that of LeBarton and Iverson that could account for these discrepancies is the fact that the fine motor scores in the latter study are a composite of scores from parent reports and standardised observations taken at different visits between 12 and 24 months. It may be that fine motor skills in this age range are more predictive of expressive language than those at 7 months, the age point in the current study, when there is less variability in fine motor abilities and more in gross motor skills, such as sitting unsupported and crawling (World Health Organization, 1993). The earlier age point was used here because significant differences have previously been reported at 7 months between these at-risk and low-risk groups in both fine and gross motor skills on the MSEL (Leonard et al., 2013). An understanding of the relationships between skills at the earliest stages of development could have important implications for screening and intervention. The current non-significant trend in the ASD-sibs subgroup, along with the similarity between the pattern of results for gross motor and fine motor skills presented in Figs. 2 and 3, suggests that there is potential for the relationship between fine motor skills and expressive language to be explored further in infants at-risk of developing ASD. A range of ages and types of assessment should therefore be used in future research to better understand the co-development of these interacting systems.

The relationship in the current data between gross motor skills and rate of expressive language growth could be due to the increased number of opportunities for developing language abilities resulting from improved gross motor skills and, therefore, locomotion around the environment. For example, the transition from crawling to independent walking seems to have a particular significance for the development of social interaction, with walking infants producing more gestures and social bids that are directed towards an adult (e.g., Clearfield, 2011; Clearfield, Osborne, & Mullen, 2008). Interestingly, it seems that these motor experiences at 7 months are not related to rate of receptive language development (or, at least, they may have a more subtle relationship that has not been identified in these analyses). This is in line with the results of Walle and Campos (2014), who reported a stronger relationship between walking (a gross motor skill) and expressive language compared to receptive language in a typically developing sample. It is possible that the amount of language heard by infants does not change dramatically with improving motor skills, meaning that the rate of development in their language understanding does not rely as much on their ability to move around their environment as does the rate of development in their language production. Alternatively, it might be due to the interaction of motor and language skills with other aspects of the social environment, such as parent involvement (Walle & Campos, 2014). It will be important to further unpick any relationship that might be present between motor skills and receptive language development, using more fine-grained behavioural techniques in these at-risk samples, so that the relationship between the very early stages of motor behaviour and receptive language can be further investigated.

While previous research has suggested a relationship between motor development and language skills in typically developing infants and children (e.g., Alcock & Krawczyk, 2010; Cheng et al., 2009; Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014; Wang et al., 2012), it was somewhat surprising that this relationship was not significant in the current low-risk group. This could perhaps be due to reduced variability in the low-risk sample, and the fact that general developmental level was included in the current analyses, as well as the different ages at which motor skills were investigated across the studies (as discussed in relation to the study by LeBarton & Iverson, 2013, previously). However, it is again important to note the differences between the methods used for assessing motor development in the current sample compared to these previous studies with typically developing samples. For example, some studies have used a single motor milestone as a predictor of expressive language (e.g., Oudgenoeg-Paz et al., 2012; Walle & Campos, 2014), while others have conducted the analyses on data from the same type of assessment, i.e., motor and language skills from one or more standardised assessments (Cheng et al., 2009), or one or more parent questionnaires (Wang et al., 2012). In the one study in which motor skills were assessed through a standardised task and language through a parent report, as in the current study, no significant correlation was found in a typically developing sample, despite significant correlations between motor and language skills when both were assessed by parent report (Alcock & Krawczyk, 2010). Finding a correlation between scales from the same instrument may be due to correlated measurement error, as the same individual (e.g., the caregiver) is reporting on both behaviours. Furthermore, the difference between results for the current low-risk group and previous typically developing samples may be due to the analysis of the impact of motor skills on the *rate* of language development in the current paper, as opposed to language *outcomes* investigated in previous studies. This is a novel addition to the literature and may therefore produce slightly different relationships than those previously reported. It may also provide greater insight into the range of alternative developmental trajectories that could lead to atypical language outcomes in infants at-risk of ASD (e.g., Karmiloff-Smith, 1998, 2009). The result will need to be replicated with a larger low-risk sample with a greater range of variability to confirm the pattern in the current study, but the methods and analyses used are an important addition to this research area.

The data presented in the current paper have important implications, as they underline the impact that early motor delays could have on the rate of expressive language development and, in turn, on social interaction and peer relationships. This is of particular interest in children who are later diagnosed with ASD, as it is precisely these difficulties in social communication that form part of their diagnoses. While there was no significant difference in the relationship between motor skills and rate of language development in the at-risk infants who did and did not later receive a diagnosis of autism, examination of Figs. 2 and 3 revealed that the pattern for the NoASD-sibs was much more similar to the low-risk group than the ASD-sibs. This 'intermediate' pattern in at-risk infants who do not develop ASD has been reported elsewhere (e.g., Elsabbagh et al., 2012), and may reflect subclinical characteristics associated with the Broader Autism Phenotype (Bolton et al., 1994). Increasing the sample size of each of the subgroups within the at-risk group could provide greater power to detect these differences, and it will be important to do so in future research in order to fully understand the implications of these results for the later diagnosis of ASD.

5. Conclusions

The relationship between motor skills and the development of a range of other abilities, including language, is receiving increasing attention in research and provides a potential window into atypical functioning in a number of neurodevelopmental disorders. By conceptualising the motor system as one component of a dynamic systems framework (Thelen & Smith, 1994), research can be focused on the interactions between systems rather than the isolated development of motor or language skills. This is important as it allows more detailed investigation of shared mechanisms and neural substrates for different skills, and also highlights how a small disruption to one system early in development can destabilise the network and have cascading effects on a number of seemingly unrelated functions (Thelen & Smith, 1994). In terms of practice, the current data are of great importance to clinicians and pre-school practitioners, who could improve functioning in a number of areas through early recognition of delayed or atypical motor development, which is increasingly reported in children and adults with ASD. Future research using larger prospective samples, as well as more fine-grained assessments during critical periods of language and motor development, will allow more complex modelling of the relationship between motor and language abilities. This will be necessary to unpick the relative importance of different motor skills on the rate of language development at different points in developmental time and to provide clear strategies for practitioners in terms of screening and intervention.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.rasd.2014.12.012.

References

Alcock, K. J., & Krawczyk, K. (2010). Individual differences in language development: Relationship with motor skill at 21 months. *Developmental Science, 13*, 677–691.

American Psychiatric Association (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.

Bhat, A. N., Galloway, J. C., & Landa, R. J. (2012). Relation between early motor delay and later communication delay in infants at risk for autism. *Infant Behavior and Development, 35*, 838–846.

Bhat, A. N., Landa, R. J., & Galloway, J. C. (2011). Current perspectives on motor functioning in infants, children, and adults with autism spectrum disorders. *Physical Therapy, 91*, 1–14.

Bishop, D. V. M. (1997). Cognitive neuropsychology and developmental disorders: Uncomfortable bedfellows. *The Quarterly Journal of Experimental Psychology Section A, 50*(4), 899–923.

Bolton, P., MacDonald, H., Pickles, A., Rios, P., Goode, S., Crowson, M., et al. (1994). A case–control family history study of autism. *Journal of Child Psychology and Psychiatry, 35*, 877–900.

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

Charman, T., & Baird, G. (2002). Practitioner review: Diagnosis of autism spectrum disorder in 2- and 3-year-old children. *Journal of Child Psychology and Psychiatry, 43*, 289–305.

Cheng, H., Chen, H., Tsai, C., Chen, Y., & Cherng, R. (2009). Comorbidity of motor and language impairments in preschool children in Taiwan. *Research in Developmental Disabilities, 30*, 1054–1061.

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.

Constantino, J., Zhang, Y., Frazier, T., Abbacchi, A. M., & Law, P. (2010). Sibling recurrence and genetic epidemiology of autism. *American Journal of Psychiatry, 167*, 1349–1356.

Curran, P. J., & Hussong, A. M. (2003). The use of latent trajectory models in psychopathology research. *Journal of Abnormal Psychology, 112*, 526–544.

Elsabbagh, M., Gliga, T., Pickles, A., Hudry, K., Charman, T. C., Johnson, M. H., et al. the BASIS Team. (2013). The development of face orienting mechanisms in infants at-risk for autism. *Behavioural Brain Research, 251*, 147–154.

Elsabbagh, M., & Johnson, M. H. (2010). Getting answers from babies about autism. *Trends in Cognitive Sciences, 14*(2), 81–87.

Elsabbagh, M., Mercure, E., Hudry, K., Chandler, S., Pasco, G., Charman, T., et al. (2012). Infant neural sensitivity to dynamic eye gaze is associated with later emerging autism. *Current Biology, 22*, 1–5.

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.

Goodman, R., Ford, T., Richards, H., Gatward, R., & Meltzer, H. (2000). The development and well-being assessment: Description and initial validation of an integrated assessment of child and adolescent psychopathology. *Journal of Child Psychology and Psychiatry, 41*, 645–655.

Karasik, L. B., Tamis-LeMonda, C. S., & Adolph, K. E. (2011). Transition from crawling to walking and infants' actions with objects and other people. *Child Development, 82*, 1199–1209.

Karmiloff-Smith, A. (1998). Development itself is the key to understanding developmental disorders. *Trends in Cognitive Sciences, 2*, 389–398.

Karmiloff-Smith, A. (2009). Nativism vs neuroconstructivism: Rethinking the study of developmental disorders. *Developmental Psychology, 45*, 56–63.

Kim, H. U. (2008). Development of early language and motor skills in preschool children with autism. *Perceptual and Motor Skills, 107*, 403–406.

Landa, R., & Garrett-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). Motor skill predicts expressive language in infant siblings of children with autism. *Developmental Science, 16*, 815–827.

Leonard, H. C., Elsabbagh, M., & Hill, E. L. the BASIS team. (2013). Early and persistent motor difficulties in infants at-risk of developing autism spectrum disorder: A prospective study. *European Journal of Developmental Psychology, 11*, 18–35.

Leonard, H. C., & Hill, E. L. (2014). The impact of motor development on typical and atypical social cognition: A systematic review. *Child and Adolescent Mental Health*. http://dx.doi.org/10.1111/camh.12055

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

Lord, C., Rutter, M., DiLavore, P. C., & Risi, S. (2000). *Autism diagnostic observation schedule – Generic*. Los Angeles: WPS.

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.

Mullen, E. M. (1995). *Mullen scales of early learning*. Oxford: NCS Pearson Inc.

Muthén, L. K., & Muthén, B. O. (2011). *Mplus user's guide* (6th ed.). Los Angeles, CA: Muthén & Muthén.

Oudgenoeg-Paz, O., Volman, M., & Leseman, P. (2012). Attainment of sitting and walking predicts development of productive vocabulary between ages 16 and 28 month. *Infant Behavior and Development, 35*, 733–736.

Ozonoff, S., Young, G. S., Carter, A., Messinger, D., Yirmiya, N., Zwaigenbaum, L., et al. (2011). Recurrence risk for autism spectrum disorders: A baby siblings research consortium study. *Pediatrics, 128*, e488–e495.

Rosenbaum, D. (2005). The Cinderella of psychology. The neglect of motor control in the science of mental life and behaviour. *American Psychologist, 60*, 308–317.

Rutter, M., Bailey, A., & Lord, C. (2003). *Social communication questionnaire*. LA: WPS.

Sparrow, S. S., Cicchetti, D. V., & Balla, D. A. (2005). *Vineland Adaptive Behavior Scales* (2nd ed.). Oxford: NCS Pearson Inc.

Tamis-LeMonda, C. S., Adolph, K. E., Lobo, S. A., Karasik, L. B., Ishak, S., & Dimitropoulou, K. A. (2008). When infants take mothers' advice: 18-month-olds integrate perceptual and social information to guide motor action. *Developmental Psychology, 44*, 734–746.

Thelen, E., & Smith, L. B. (1994). *A dynamic systems approach to the development of cognition and action*. Cambridge, MA: MIT Press.

Toth, K., Dawson, G., Meltzoff, A. N., Greenson, J., & Fein, D. (2007). Early social, imitation, play, and language abilities of young non-autistic siblings of children with autism. *Journal of Autism and Developmental Disorders, 37*, 145–157.

Walle, E. A., & Campos, J. J. (2014). Infant language and development is related to the acquisition of walking. *Developmental Psychology, 50*, 336–348.

Wang, M. V., Lekhal, R., Aarø, L. E., & Schjolberg, S. (2012). Co-occurring development of early childhood communication and motor skills: Results from a population-based longitudinal study. *Child: Care, Health and Development*. http://dx.doi.org/10.1111/cch.12003

World Health Organization (1993). *The ICD-10 classification of mental and behavioural disorders. Diagnostic criteria for research*. Geneva: WHO.

World Health Organization, & WHO Multicentre Growth Reference Study Group (2006). WHO motor development study: Windows of achievement for six gross motor development milestones. *Acta Paediatrica Supplement, 450*, 86–95.