Oral motor and gesture abilities independently associated with preschool language skill - Longitudinal and concurrent relationships at 21 months, 3 and 4 years

Katie Alcock

Department of Psychology, Lancaster University

Simon Connor

Department of Psychology, Lancaster University and Simon Connor Psychological Services Ltd

Address for correspondence

Correspondence concerning this article should be addressed to Dr Katie Alcock, Department of Psychology, Lancaster University, Fylde College, Bailrigg, Lancaster LA1 4YF. Email: k.j.alcock@lancaster.ac.uk

Conflict of interest: There are no conflicts of interest, financial or otherwise.

Funding: The baseline study was supported by an ESRC small grant (RES-000-22-0054) to the first author. The 3 and 4 year data collection was supported by a Lancaster University PhD studentship awarded to the second author.

Abstract

Purpose: Early motor abilities (gesture, oral motor, and gross/fine skills) are related to language abilities, and this is not due to an association with cognitive or symbolic abilities: oral motor skills are uniquely associated with language abilities at 21 months. It is important to determine whether this motor-language relationship continues beyond the earliest stage of language development, to understand language acquisition better, and better predict which children may have lasting language difficulties.

Method: In this longitudinal study we assessed language comprehension and production, oral motor skill, gross/fine motor skill and meaningless manual gesture, at 3 years (N=89) and 4 years (N=71), comparing the contribution of motor skill, and earlier (21 month) language ability. We also examined covariates: non-verbal cognitive ability, socio-economic status, and stimulation in the home as measured on the Home Screening Questionnaire.

Results: Motor abilities continue to have a significant relationship with language abilities independent of other factors in the preschool years. Meaningless manual gesture ability, gross/fine motor skill and oral motor skill were still associated with language skill at 3y; these relationships are not explained by the contribution of cognitive abilities or earlier language abilities.

Conclusions:

Relationships between early motor skill and language development persist into preschool years, and are not explained by other cognitive or home factors, nor by a relationship with earlier language ability. This finding should lead to a better understanding of the origins of language abilities.

Oral motor and gesture abilities independently associated with preschool language skill - Longitudinal and concurrent relationships at 21 months, 3 and 4 years

Motor and language abilities

Early motor abilities have a close relationship with developing language. Early motor abilities have several components: these include a) *gesture*, communicative or non-communicative. The onset of this is highly associated with the age at which spoken words are first seen (Bates, 1980) and there seems to be an evolutionary as well as developmental association between the two (Volterra, Caselli, Capirci, & Pizzuto, 2005). Developmental language disorders also have a relationship with disorders of motor control (Bishop, 2002; Botting, Riches, Gaynor, & Morgan, 2010; Brumbach & Goffman, 2014; Hill, 1998). In particular, data from these research groups show that gesture appears to be more closely linked to language skill than b) *fine or gross motor skill*, a second aspect of early motor abilities.

In children with Specific Language Impairment (SLI, also known as Developmental Language Disorder, DLD), deficits in motor skills can give us clues as to what aspects of motor ability are closely related to language ability. Some studies have looked at gesture ability (also known as praxis) and some at gross/fine motor skill and some at both. Dewey and Wall (1997), Hill (1998), Botting et al. (2010) and Wray, Norbury, and Alcock (2016) all found that gesture was impacted in children with DLD and, where gesture and fine motor skill were both tested, gesture was impacted separately to the effect of fine motor skill, if tested. In Hill (1998) it appears that the effects on both skills were tested but not statistically separated from each other. Brumbach and Goffman (2014) found that motor control was affected but did not test gesture, and the same applies to Zelaznik and Goffman (2010) and Sanjeevan et al. (2015).

This body of work backs up the rationale for investigating gesture as well as other aspects of motor skill in looking at typically developing children's language. Based on our findings at the baseline time point (Alcock & Krawczyk, 2010) and on previous data showing gesture is more closely associated with language than gross/fine motor skill (where both are tested) we decided to reduce testing burden on the children in this unplanned follow-up study, and to directly test only gesture and oral motor skill, which seemed the most promising of the skills from our previous time point. Although it is true that there are some findings of impaired gross/fine motor skill in children with atypical language development (Sanjeevan et al., 2015; Zelaznik & Goffman, 2010), there is also a more general finding of a lack of relationship between gross/fine motor skill and language development in the broader typical range (Bates, 1980).

Looking at mechanisms, Iverson (2010) reviews and discusses these for early links between language and early motor skill (mainly gesture and fine/gross motor skill). As infants' limb movements become more rhythmic, this paves the way for linguistic rhythmic movements - babble. Acting on objects to combine them coincides with first words; and infants combine words and gesture to make their first communicative combinations, before they can combine two words. This explanation is highly functional. Different aspects of motor and language development provide practice to enhance each other; independent locomotion provides increased opportunities for interaction with the world and with conversational partners. Following on from Iverson's review, her group has uncovered many predictive and concurrent relationships between limb motor skills and communicative abilities (Iverson & Braddock, 2011; LeBarton & Iverson, 2013, 2016), including in at-risk groups such as preterm infants and younger siblings of children with autism spectrum disorder (LeBarton & Iverson, 2016; West, Leezenbaum, Northrup, & Iverson, 2019).

Other explanations involve the communicative and/or symbolic nature of many gestures. Early gesture skill – including symbolic and deictic – is highly correlated with early language skill, and this has been hypothesised to be both because children use their emerging symbolic language skills to develop their gesture skill, and because their motor and language skills seem to rely on a shared substrate (Bates, Thal, Whitesell, & Fenson, 1989). Iverson and Thelen (1999) review a variety of possible mechanisms for the language/motor link in development and in mature language use and suggest that common and adjacent neural substrates and common reliance on timing control are both important to consider in researching this link. The class of explanations involving a common underlying timing mechanism helps to explain the transition from babbling to words noted by Esteve-Gibert and Prieto (2014) to involve linked gesture-speech timing.

There is little work to date on meaningless gesture, however; this involves the copying of gestures that are not (or not yet) associated with a communicative or symbolic meaning by the child. In learning gesture in everyday life, children must learn most gestures from an example given by an adult, which may not have a meaning associated with it yet. This means that copying "gestures with no meaning yet" is a useful skill for a child. If these are related to language development could help us to distinguish between mechanisms; if early non-symbolic (or meaningless) gesture is related to early language, it is possible that it is not the *symbolic* nature of early gesture that links it to early language, but either the linked neural substrates and/or common timing mechanisms. We can hence rule out the symbolic explanation by looking at meaningless gestures, but cannot necessarily discriminate between other explanations.

While many of these authors refer mainly or exclusively to control of limb movements, a third type of motor skill, c) *oral motor skills* are also implicated in the developing motor/language relationship. Alcock and Krawczyk (2010) found that oral motor skills – children's ability to imitate and coordinate mouth movement skills without speech content – were related to language production at the age of 21 months, independently of relationships with limb motor skills and cognitive skills. Davis and MacNeilage (1995) found common oral movements in pre-speech babble and in early speech; building on this body of work, parallel developments can be seen in spontaneous non-speech and early speech movements in many subsequent data sets, though not between feeding and pre-speech movements (Nip, Green, & Marx, 2011; Steeve & Moore, 2009). Neither is the contribution of oral motor skills to speech and language solely due to a common short term memory component (Krishnan et al., 2017). Data from adults shows that stimulation that disrupts sequences of oral movements also disrupts naming and reading (Ojemann, 1984). Again, further associations between oral movements and language development would help to eliminate a symbolic background to the motor/language relationship, and add strength to the explanations of linked neural substrates or common timing mechanisms.

Children with a variety of disorders that affect some aspects of spoken language also have some nonverbal oral motor difficulties, including children with developmental verbal dyspraxia (Alcock, Passingham, Watkins, & Vargha-Khadem, 2000), autism (Gernsbacher, Sauer, Geye, Schweigert, & Hill Goldsmith, 2008) and Williams Syndrome, where spoken language is delayed in onset (Krishnan, Bergström, Alcock, Dick, & Karmiloff-Smith, 2015). We additionally found (Alcock & Krawczyk, 2010) concurrent relationships between oral motor skill and language development at the age of 21 months, across the range of individual differences in typical language development. Why is it important to examine relationships with individual differences?

Individual differences in language acquisition

Children vary in their rate of acquiring language (Fenson et al., 2000), with some children starting to talk significantly later than others and some of these continuing to show language delay (Rescorla, 2011). Some of these children will show long term difficulty in spoken and written language (Rescorla, 2002). Other children are precocious, early talkers which by some accounts is not a stable characteristic, but in other studies seems to be a predictor of precocious literacy skills (Dale, Crain-Thoreson, & Robinson, 1995; Skeat et al., 2010).

Investigating the relationship of other skills to developing language skill can enable us to find out more about how language develops, and how to predict which children might be delayed or precocious language users. In our baseline study (Alcock & Krawczyk, 2010) we examined language, oral motor, gesture, fine and gross motor and cognitive abilities at the age of 21 months, a time of rapid language development. Although opinions vary about whether the quality of language development differs at this time (Ganger & Brent, 2004), choosing a time point when children's vocabulary sizes are very different to each other means it is easier to detect individual differences.

The current study

This study builds on the work of Alcock and Krawczyk (2010), who showed that oral motor skill is independently associated with language ability at 21 months. We investigate here the longitudinal relationships between motor (oral motor, gross and fine motor, and gestural ability) and language skills at 21 months and those at 3 and 4 years of age. Concurrent skills are clearly more likely to be associated with each other. Crucially, if skills are associated over a longer period of time, and/or at multiple time points, this can tell us more about the mechanisms of children's language development in general, over and above a simple association at one time point. We hypothesise that motor skills will continue to be associated with language skills at multiple time points; this may mean that earlier motor skills predict later language skills and/or that similar relationships between motor and language skills are found at more than one time point.

Because many different factors are likely to influence language development, and we need to ensure we are not measuring artefacts, we controlled for nonverbal cognitive abilities (we include here symbolic cognitive abilities and auditory processing abilities, which may also make equal or stronger contributions to language development, so we need to factor these out), as well as stimulation in the home and socio-economic status (SES). In our original cross-sectional study we found that gesture, fine motor and gross motor skills did not have a separate relationship with language skills over and above the contribution of oral motor skills or vice versa (Alcock & Krawczyk, 2006). However, given the strong relationship between early gesture and language skills (Bates et al., 1989; Volterra et al., 2005), it seemed likely that some independent associations between limb motor control and language might emerge at an older time point.

Our longitudinal study, following children to an older age than previous studies (Alcock & Krawczyk, 2010; Bates et al., 1989; Volterra et al., 2005) can establish this; relationships at a single age are indicative but cannot tell us anything about whether one ability *predicts* another ability (and therefore the second ability is built may build on the first) and/or whether relationships occur at different ages (and therefore the relationship *persists* through early childhood).

Hence we assessed children longitudinally on limb motor skills (manual gesture, gross/fine motor skills) and oral motor skills. At the previous time point, some children only had parent report measures available for gesture and motor skills, while others had direct measures (Bayley, 1993), but in the current study we attempted to assess all children directly on both manual gesture ability and oral motor ability. We hypothesised that motor skills would continue to have independent relationships with language abilities in the preschool years; because of our longitudinal design, we can here examine predictors rather than merely correlates. Based on our previous data and on previous literature, we suggest that finding such a relationship between meaningless gesture and/or oral motor skills on the one hand, and language skills on the other, can eliminate the possibility that a motor/language association in development exists due to a common symbolic origin of gestural and language abilities. Rather, we hypothesise that this is likely to be due to either a common neural basis, or a common basis in timing control, or both.

We examined oral motor and manual gesture skills at both follow-up time points and in addition we examined gross and fine motor skills, although we had not previously found these to be correlated with language ability (Alcock & Krawczyk, 2010), and other authors suggested that gross motor skill was not strongly related to language ability either (Bates, 1979). Although there are standardised fine and gross motor assessments available for this age group, because of the lack of relationship found at our baseline testing point, and previous work suggesting no relationship, at this point we decided to omit direct testing of this skill to reduce testing burden.

We wished to examine gestural ability at both follow up time points even though we had not seen a relationship at 21 months, as previous authors had found relationships with symbolic and non-symbolic (meaningless) gesture (Bates, O'Connell, Vaid, & Sledge, 1986). Because the symbolic gesture task used at 21 months was nearly at ceiling, we did not repeat a symbolic gesture measure at 3 years but replaced it with a symbolic comprehension task (see below). Our data were collected before those of Botting et al. (2010) but their finding of impaired symbolic gesture comprehension in DLD somewhat justifies our choice – children in Botting's study were impaired in symbolic ability even without a motor burden. We likewise chose our 4 year measures after being aware of the 3 year results, so introduced a new meaningless (non-symbolic) gesture measure, taken from Bergès and Lézine (1965).

We also sought to determine whether these relationships were due to other, more closely linked skills being associated with both language and different types of motor skills. At 21 months we found that cognitive skills were associated with language skills, independent of the motor skills often needed by young infants to perform non-verbal cognitive tasks (Alcock & Krawczyk, 2006). However, since at the first time point we did find significant independent associations between language skills and nonverbal cognitive skills (Alcock & Krawczyk, 2006) and between language skills and auditory processing skills (Alcock & Krawczyk, 2008), we tested these abilities again both to explore the relationship more generally between language and non-verbal ability (an overall aim of our original study), and to ensure we were testing as many mediators and moderators of the relationship between language and motor skills as possible. We therefore tested children on a variety of cognitive tasks - visuo-spatial tasks, auditory processing (Aslin, 1989), nonword repetition (Gathercole, 2006; Krishnan et al., 2013) - that are more or less likely to have a relationship with language development. We need to determine whether the inverse is true: children's cognitive abilities enable them to perform well on both language and motor tasks, giving an artefactual relationships if only some domains of developing skill are tested. This again mirrors our design at 21 months where we ensured that we had measures of cognitive and motor skill to disentangle the relationships of both of these areas of development to language development.

Methods

Participants and measures

Age 21 months (Time 1) Participants

Families that participated in the original study were recruited from a local hospital at the time of birth, and re-contacted aged 18 months at which time point a short Communicative Development Inventory (CDI) based on the Oxford CDI (Hamilton, Plunkett, & Schafer, 2000) was administered and children were divided into four testing groups each of which had equal numbers of children from each decile of language abilities. Families where children heard a language other than English (defined as for over one day a week) were excluded but no other families were excluded.

General testing considerations (all time points)

Children were tested in a quiet room at the Babylab, and a parent or caregiver plus a research assistant (at age 21 months) or the second author (at age 3 and 4 years) was present. Gesture and oral motor tasks were videoed at all time points. Word/non-word repetition tasks were audio recorded. All other tasks were scored as testing occurred.

Age 21 months (Time 1) Measures

Children in each testing group did a different set of tests at age 21 months, and at this age 128 families either completed some questionnaires on language and motor skills, or completed some laboratory testing plus a language questionnaire, or both. For further details of testing at 21 months see Alcock and Krawczyk (2010). However, in summary all children had data from the full Oxford CDI, as well as either motor tasks (oral motor tasks, gesture tasks, fine and gross motor tasks) or motor questionnaires (gesture, fine and gross motor) or both. Measures at Time 1 are outlined in Table 1, including N for each task.

[Table 1 about here]

Saudino et al. (1998)

Age 3 years (Time 2) Participants

At the age of 3 years, 89 children (39 girls) and their families returned for testing, with testing taking place between the ages of 2.90 years and 3.15 years (mean 3.03, SD .043).

Age 3 years (Time 2) Measures

At 3 years the Preschool Language Scale 3rd Edition (PLS-3 UK) (Zimmerman, Steiner, & Pond, 2003) was administered to all children.

Some of the same motor tasks were administered exactly as at Time 1: Oral Motor Control, Gesture Sequencing, and Meaningless Gesture tasks (Alcock & Krawczyk, 2010) to 41 children (14 girls), of whom two children refused to participate entirely. In these tasks, children imitate single movements (Oral Motor Control, Meaningless Gesture), sequences of movements with props (Gesture Sequencing) or perform single movements to command with props (Oral Motor Control). Full details of the Oral Motor and Meaningless Gesture tasks are in the Appendix. The Gesture Sequencing task is similar to that used by Thal and Tobias (1994).

The symbolic gesture task administered at Time 1 was omitted since children were nearly at ceiling at Time 1. For the Meaningless Gesture task at this age (as at Time 1 and Time 3), children were discouraged from labelling the gestures verbally, and the research assistant administering the tasks practiced demonstrating gestures so they did not resemble iconic or communicative gestures.

Parents of 83 children (37 girls) completed the Home Screening Questionnaire (HSQ, Frankenburg & Coons, 1986), a parent-completed version of the Home Observation for the Measurement of the Environment (HOME - for information see Elardo & Bradley, 1981). This instrument measures material and social stimulation in the home, including toys present, outings, and parent-child interaction.

A total of 42 children (23 girls) completed the Words section of the Preschool Repetition Test (PSRep - Roy & Chiat, 2004). All but two of those children also completed the Nonwords section; these are both tests of phonological working memory.

Finally a total of 34 children (13 girls) completed the Block Design subtest of the British Ability Scales (Elliot, Smith, & McCullouch, 1997) and 34 children (15 girls) completed the Symbolic Comprehension Assessment task (described in O'toole & Chiat, 2006; Roy & Chiat, 2005). These are tests of nonverbal cognitive ability and symbolic ability respectively.

The order of the tests was rotated so not every child did the same test first, with breaks to play in between tests. As some children discontinued testing due to fussiness or tiredness during the testing session, omitting different tests due to the rotated order, numbers for each test are uneven. Each child participated in as many tests as possible within a single session with breaks where necessary, which totalled 60-120 minutes (testing and break time). The intention was that all children did all tasks, unlike at Time 1. Descriptives for these tasks (including N for each task) are shown in Table 2.

Age 4 years (Time 3) Participants

A total of 71 children (32 girls) took place in testing at Time 3, with testing taking place between the ages of 3.95 years and 4.17 years (mean 4.05, SD .040). This represented 64 children who had taken part at Time 2, and 7 children who returned for testing only at Time 3. As can be seen from the numbers completing each task at 4 years, children were more able to sustain a longer testing period and individual missing tests are largely due to refusal on a single test rather than discontinuing testing altogether.

Age 4 years (Time 3) Measures – Language tasks

A total of 67 children (32 girls) completed the Bus Story task (Renfrew, 2001). The task was administered as suggested in the instructions and transcribed into CHAT format (MacWhinney, 2000). Type-Token Ratio, Vocabulary Diversity (VOCD, recommended by the CHILDES authors as more representative of children's vocabulary abilities at this age - MacWhinney, 2000), Mean Length of Utterance (in morphemes - MLU) and the Index of Productive Syntax (IPSyn; Scarborough, 1990) were calculated; these measures examined se mantic production, and grammatical production.

The Test of Reception of Grammar version 2 (TROG-2; Bishop, 2003) was administered to 68 children (32 girls); this measure examined grammatical comprehension.

Age 4 years (Time 3) Measures – Motor tasks

Tests of Oral Motor Control based on those administered at Time 1 and Time 2, and on those developed by Alcock et al. (2000), were administered to 65 children (32 girls). This task was more challenging than that administered at Time 2, with combinations of two or three movements, both simultaneous and sequential added to the single movements. The set of movements is shown in the Appendix and was administered in the same pseudo-randomised order (the order given in the Appendix) each time, and details of scoring are also shown in the Appendix.

A more difficult Meaningless Gesture task than at younger ages was administered to 68 children (33 girls). This consisted of a series of meaningless hand gestures, and was taken from Bergès and Lézine (1965). Full details are in the Appendix.

Finally parents of 84 children (38 girls) also completed a Motor Questionnaire adapted from the Ages and Stages Questionnaires (Squires, Potter, & Bricker, 1995; all the questions on the 48 months questionnaire asking about fine or gross motor abilties were extracted, as well as further unique questions from the 54 and 60 month scales. Some wording was changed for the UK context) which asks parents a number of questions concerning their child's gross and fine motor skills. Each question takes the form of an example, e.g. "can your child thread a lace through an eyelet". For each question, the parent (usually the mother) was required to answer "yes" "sometimes" or "no". Answers were scored two points for "yes" one point for "sometimes" and no points for "no". This questionnaire was originally designed as a screening questionnaire but has been validated in a variety of settings against standardised assessments (for example, Schonhaut, Armijo, Schönstedt, Alvarez, & Cordero, 2013). In our sample scores on this questionnaire at 21 months correlated significantly with scores on the gesture questionnaire (taken from the MacArthur-Bates Communicative Development Inventory, Fenson et al., 1994, which has additionally been validated in a laboratory setting).

Age 4 years (Time 3) Measures – Cognitive tasks

A total of 67 children (31 girls) completed the Block Design subset of the British Ability Scales (Elliot et al., 1997), which measures nonverbal cognitive ability.

A total of 57 children (28 girls) completed an Auditory Discrimination task. This was a task designed to test children's ability to discriminate between frequency sweeps of the type described in Aslin (1989), which are hypothesised to be similar to speech sound transitions. Nine non-verbal auditory stimuli were also created, consisting of 50msec pure tone upward transitions immediately followed by a 250 msec static frequency 1000Hz pure tone with 20 msec fade in and out included in all stimuli. The comparison tone was a 350Hz transition i.e. starting at 650Hz, followed by a steady tone) and the test tones were 25Hz, 50Hz, 75Hz, 100Hz, 150Hz, 200Hz, 250 Hz, and 300Hz i.e. starting at between 975Hz and 700 Hz, followed by a steady tone. Hence the test tone 25Hz is the furthest from the comparison tone and the test tone 300Hz is closest; a child who can discriminate the 25Hz tone from the comparison tone is performing the easiest task while a child who can discriminate the 300Hz tone from the 350Hz tone is performing the hardest task.

Children saw a visual display with three pictures of "aliens", and were told that the aliens were a Mummy, a Daddy and a Baby. Each alien was animated so that its "mouth" moved as the sweep was played, and each alien "spoke" (produced a test or comparison tone) 3 times in succession. The child was told that all three aliens would "speak", that the baby alien was trying to learn to speak, and that the child's job was to tell the experimenter whether the baby had spoken like the Mummy or the Daddy. One "parent" spoke first, then the "baby", then the other "parent" on each trial. The child's task was therefore to compare the "baby" to the sound immediately before and that immediately after, minimising memory load.

The child therefore had to match the "baby's" tone to one of the "parents'" tones, and one "parent" on each trial (randomly allocated) produced the 350Hz comparison tone. The assessment followed a two up one down paradigm, so that when the child got two answers correct, the difficulty would increase (a tone closer to the comparison tone would be played), but when the child got a single answer wrong then the difficulty would decrease (a tone further from the comparison tone would be played). The Auditory Discrimination task was discontinued at the point when the child had three reversals in direction of difficulty at any point in the task. The score for each child was then the mean frequency of the three reversal trials or, in the case of a child who successfully identified the 300Hz tone three times, the score was 300. The code for the Auditory Discrimination task was written in Psyscript, a proprietary experiment administration language (Slavin, 2007), but is available on request.

Results

Data availability

The full dataset will be made available in online Supplementary Materials.

Analysis

We sought to examine the longitudinal and cross-sectional relationships of Time 1 (21 months) factors with Time 2 (3 years) language abilities (Analysis 1). We also sought to examine, separately, the longitudinal and cross-sectional relationships of Time 1 and Time 2 factors with Time 3 (4 years) abilities. Because many scores are available only for some children, analyses are carried out firstly on as many children as possible for most comparisons (using pairwise deletion), but for combinations where this is not possible (e.g. some correlations between 21 month scores and 4 year scores have as few as 11 children) this correlation had to be excluded from the analysis.

Time 1 and Time 2

Descriptives Time 2 (age 3)

Table 2 shows descriptives (mean, SD, minimum and maximum score achieved, and maximum possible score where relevant) for the following tests at 3y: PLS Expressive, Auditory and Total, Oral motor test total and complex movements scores; Meaningless Gesture and Gesture Sequences; the HOME questionnaire; Symbolic Comprehension, Block

Design, and the PSRep task.

[Table 2 about here]

Zero-order correlations

Correlations between on the one hand 21 month language, cognitive and motor measures, and 3 year motor and cognitive measures (as well as SES measures), and on the other hand 3 year language outcomes, were carried out. These are shown in Tables 3 and 4. Holm-Bonferroni corrections (Holm, 1979) were carried out within each table, and those correlations that remained significant are marked. Tables 2 and 3 show the number taking part at 3 years and the number of these who took part longitudinally in each set of measures between 21 months and 3 years; these range from 84 out of 89 3-year participants having language measures at both time points to 16 having 21-month Meaningless Gesture as well as 3-year PLS.

Broadly, 21 month language measures were significantly associated with 3 year language measures, and 3 year Oral Motor Control, cognitive, HSQ, Motor Questionnaire and Meaningless Gesture was associated with 3 year language measures.

21 month gross and fine motor measures were not significantly associated with 3 year language measures, and nor were 21 month cognitive or SES measures.

[Tables 3 and 4 about here]

Regression analyses predicting Time 2 – 3y

Regression analyses were carried out with each of three separate measures of 3 year language abilities (expressive scale of the PLS, auditory comprehension scale of the PLS, and total PLS score) as the dependent measure. Language measures from 21 months that were significantly correlated with the dependent measure were entered at the first step, and measures taken at 3 years at the second step.

Where two measures appeared to be collinear, the Variance Inflation Factor (VIF) was noted and if this exceeded 2.5 for any measure the higher VIF measure was removed from the analysis (see Model 6 for example where CDI Production was removed).

Because of overlapping subsets of children who completed different tasks at 3 years, insufficient children completed all of the oral motor, gesture, symbolic and PSRep tasks to enter all these variables, together with the HSQ, into a single regression analysis. Therefore, after the regression was carried out with the 21 month language, and 3y motor variables, additional regressions were carried out with the same 21 month predictor variables but with the additional cognitive/HSQ 3y predictor variables entered individually. This approach also avoids some collinearity.

Significant regression models are shown in Table 5.

[Table 5 about here]

In summary, even after examining and controlling for the effects of earlier motor and language abilities, concurrent oral motor abilities still have a significant relationship with language production (and with total score on the PLS) at 3 years, which replicates the result of Alcock and Krawczyk (2010) – Models 1 and 5. In addition, although at Time 1 no remaining significant relationship was found between any type of gesture or gross/fine motor skills and language abilities, at Time 2 all of earlier language comprehension, concurrent Meaningless Gesture abilities and concurrent Motor Questionnaire scores (gross and fine motor abilities) have a significant relationship with language comprehension abilities – Model 3. Finally, concurrent relationships between language at 3y and cognitive measures and HSQ do not appear to be independent of earlier language or motor measures – Models 2, 4 and 7.

Models 3 and 5 are shown in Figure 1. Model 1 is identical in form to Model 5 so is not shown.

Time 1, Time 2 and Time 3

Descriptives Time 3 (age 4y)

Descriptives for 4y measures are shown in Table 6.

[Table 6 about here]

Zero order correlations

Correlations between 4y (Time 3) language outcomes – score on the TROG, and the Type-Token Ratio (TTR) Vocabulary Diversity (VOCD), Mean Length of Utterance (MLU) and Index of Productive Syntax (IPSYN) from the Bus Story narratives – and 21 month and 3y language measures are shown in Table 7, as are correlations between Time 3 language outcomes and Time 1 motor and cognitive measures. Correlations between Time 3 language outcomes and Time 2 motor and cognitive measures are shown in Table 8; and correlations between Time 3 language outcomes and Time 3 nonverbal measures (Oral Motor Control, Meaningless Gesture, nonverbal cognition, Auditory Discrimination) are shown in Table 9. Within each set of correlations, Holm-Bonferroni corrections were carried out and correlations that remained significant are marked. Again, tables 6, 7 and 8 give an indication of the numbers on each test longitudinally; these range from 64 with 21 month language and 4 year language data to 11 with 21 month oral motor and 4 year language data.

[Tables 7 8 and 9 about here]

In summary, the TROG was associated with one language measure, and the HSQ, while IPSYN was associated with earlier Symbolic Comprehension and with concurrent oral motor skills. Type-Token Ratio, VOCD and MLU were not significantly associated with earlier or concurrent measures once we accounted for multiple comparisons.

Regression analyses predicting Time 3 – age 4y

Regression analyses were carried out to determine independent variables associated with children's TROG score (language comprehension) and IPSYN (language production) at Time 3.

As above, for each model analysing the associates of one outcome language measure at Time 3, measures from an earlier time point (CDI Comprehension for TROG and Symbolic Comprehension for IPSYN) were entered into the regression analysis at Step 1. Following this, measures from a later time point (the 3y HSQ and the 4y oral motor measure respectively) that were significantly associated with the outcome measure were entered into the model at Step 2.

In summary, at age 4y, the HSQ (a checklist administered at age 3y; owing to lack of parallel data at other time points we have had to presume this is representative of the home environment throughout the study) remains predictive of 4y receptive language (TROG) over and above earlier language abilities. The 4y measure of language production (IPSYN) is associated with 3y Symbolic Comprehension after concurrent (4y) oral motor ability is accounted for.

These two significant models, Model 1 and Model 2, are shown in Figure 2 and in Table 10.

[Table 10 about here]

Dropout characteristics

With a relatively large dropout rate (30% by age 3), it is helpful to know if the continuing versus dropped out participant families differ in some ways. Index of Multiple Deprivation, IMD (Office of National Statistics, 2004), a score indicating the total number of deprivation indicators in the child's home postcode, did not differ between continuing and dropout families at either time point (Mann-Whitney $U = 1648.5$ for 3 years, $U = 1780$ for 4 years, n.s.; note the median IMD for England is 21.64, mean 16.98; and the median for our families is 13.11, mean 16.14. Our families were significantly less deprived than English residents as a whole, $t(129.61) = 6.37$, $p < .001$). Children who continued in the study knew the same number of words at 21 months as those who did not continue, CDI Production t

(119) = .718, CDI Comprehension $t(119) = .123$, n.s.

As reported at the end of the Results for Time 2 and Time 3, the numbers that were tested longitudinally on each domain varied (many more children had longitudinal data for language scores than for e.g. motor scores, which probably reflects the CDI data collected at Time 1 for all children where other domains were assessed directly).

Discussion

In summary, our longitudinal study has shown that oral motor skills are still associated with language production ability at 3 years of age, independent of relationships between language production and other abilities. Likewise, meaningless gesture skills and gross/fine motor skills are also associated with language comprehension ability at 3 years, as well as (but not due to) a relationship between earlier (21 months) language comprehension and language comprehension at 3 years. These relationships are also not due to underlying symbolic abilities (the motor measures were all selected not to have symbolic content, and the symbolic comprehension task was not related to language ability). We can therefore conclude that an alternative explanation is that children need good motor skills to develop good language skills. This fits with Iverson and Thelen (1999)'s idea, and our hypothesis, that the motor-language link in development is due to either overlapping neural representation or common underlying mechanisms such as timing.

This replicates our finding of motor-language links at 21 months, where we also found non-symbolic motor abilities (our Oral Motor Control measure) were associated with language abilities, independent of other correlates of language. An independent relationship at two time points is also indicative of an underlying common foundation for both sets of skills, rather than contribution of earlier language ability to both earlier motor and later language abilities.

At 4 years we found a new significant relationship between 4y receptive language and the HSQ; neither this nor other measures of home environment or SES had any significant relationship with language at earlier ages. For language production at 4 years, we also found a new independent relationship between symbolic abilities (the Symbolic Comprehension Assessment, Roy & Chiat, 2005) and IPSYN.

Motor, language and cognitive skills

At our earliest testing point, children's nonverbal cognitive skills were also independently associated with their language abilities, but these did not explain the association between motor skills and language abilities, nor vice versa (Alcock & Krawczyk, 2006). Other work has suggested that motor and language skills are associated because of the symbolic nature of gesture (Bates & Dick, 2002; Bates et al., 1989), but our findings show that this is not the case. At 21 months symbolic ability was independent of motor and language associations, and in addition the motor skill that was still significantly associated with language skill after controlling for other measures was our Oral Motor Control measure – which does not as far as we can see contain a symbolic element. Likewise, a conceptual or visuospatial component does not explain this relationship – the motor/language relationships are statistically independent of any nonverbal or visuospatial abilities.

We have replicated this finding (the separate associations of cognitive and motor skills with language abilities) at Time 2 and Time 3. Despite various measures of cognitive skills being employed at Time 2 (3 years), none of these measures explained the significant associations between motor abilities and language abilities. Our battery of tests at each age eliminated these possibilities and our findings justify our choice to assess this wide range of children's non-verbal abilities.

Furthermore, the remaining significant associations were with our Meaningless Gesture task and our Gross/Fine motor questionnaire (relationship with receptive language at 3 years; note that neither of these measures were associated with language at 21 months) and with Oral Motor Control once again (relationship with expressive language at 3 years). Again, it is hard to see that these motor abilities contain symbolic content. Relationships between cognitive and environmental factors, and language abilities, at 4 years, underline the independence of these factors from motor abilities, and from earlier predictive language abilities. In order to fully examine the underpinnings of language development, it is essential to examine motor skills – both oral motor and limb motor skills, not purely cognitive/symbolic skills that include a motor component – at a variety of ages. We need to include motor skills in any studies examining language development and its associates or we will never be able to discriminate the associations of other tasks – that include a motor component – from the associations between motor and language skills.

At the 21 month time point we assessed symbolic and non-symbolic (meaningless) gesture. At 3 and 4 years we only assessed non-symbolic gesture, but we assessed symbolic abilities at 3 years using a comprehension task. Other research (Botting et al., 2010; Hill, 1998) found that symbolic gesture was impaired in children with DLD but given the mixed findings, and the fact that symbolic comprehension was also impaired, and our focus on oral motor skills following on from our 21 month findings, we decided not to assess symbolic gesture production at 3 or 4 years; this is a weakness of the study. We feel that the lack of symbolic contribution to the gesture-language link at 3 years, however, somewhat mitigates this weakness.

Botting's study found impairment in comprehension of symbolic gesture, too, but symbolic abilities do not explain our motor-language links. Unlike previous studies, we can also separate the effect of gross/fine motor skills from the effect of other types of motor control: Sanjeevan and Mainela-Arnold (2017) and Zelaznik and Goffman (2010) found impairments in gross/fine motor abilities in children with DLD, but did not also test gesture. We found a separate link between all of gross/fine motor abilities, oral motor and gestural ability, and language abilities. We can thus distinguish between the links from all these motor abilities to language ability in this typically developing sample.

Oral motor skill, nonword repetition and language abilities

Many previous studies have shown that nonword repetition abilities are closely associated with language skill (Gathercole, 2006), and that this association is related to the oral motor/language link (Krishnan et al., 2013). We did not find a relationship between word/nonword repetition abilities and language abilities at 3 or 4 years, after correcting for multiple comparisons. However, the number of children who completed the 3y repetition task was limited (especially when we look at those who also completed the 4y language measures), so this negative finding must be interpreted with caution.

Continuing participation in longitudinal testing

At 21 months, we recruited 128 families for participation, who all completed the CDI measure. Because of the design at this time point, some of the direct testing measures were not completed by all of the children, but at 3y and 4y all children were selected to complete all lab testing measures. However, only 89 children returned for testing at 3y (30% dropout) and of those 64 returned at 3y and 7 Time 1-only participants returned. With children's varying participation due to willingness, tiredness etc. at Time 2 and Time 3, some Ns for analyses become very small and this limits the power of our analyses. This is reflected in the Ns for individual domains tested longitudinally, with some (such as language at 21 months to language at 3 years) having Ns over 80 but some (such as motor skills at 21 months to language at 4 years) having Ns under 15.

The project as commenced at Time 1 was not intended as a longitudinal project and families who signed up were not aware that we would be contacting them at Time 2 and Time 3, because this was not planned at the outset (though all those re-contacted gave permission to be contacted for other studies). This may have reduced participation at Time 2 and Time 3 (indeed, the fact that some families were willing to participate at Time 3, but presumably were not contactable or could not arrange testing in a timely manner at Time 2, suggests that they were willing but unable due to logistical reasons, and were not simply dropouts). Nevertheless, a 30% dropout rate after 15 months have elapsed is disappointing, but it is reassuring that the dropouts seem to have been randomly distributed with respect to both SES and language skill at 21 months.

Conclusions

In conclusion, we have found new relationships between motor and language skills in our longitudinal study: speech and language development across the typically developing range is closely associated with both manual and oral motor skills. Of particular interest are our findings relating to Meaningless Gesture and Gross/Fine motor skills, and language comprehension at 3 years, a new relationship at this time point, not seen at baseline. This association cannot be accounted for with reference to oral motor skill, visuospatial ability, symbolic ability or other nonverbal cognitive abilities.

The Meaningless Gesture tasks involve some degree of verbal command (though we attempted to minimise children's opportunity for recoding movements verbally by discouraging labelling) and all of the movements are performed to imitation. It is certainly possible that this imitation skill provides a common core for both language comprehension and for imitation of meaningless gesture. The parent questionnaire for gross/fine motor skills also includes an element of imitation (as parents are asked to try items they are not sure if their child can do by demonstrating them).

Other, non-motor tasks that involve imitation were not administered at 3y or 4y (though it could be argued that, for example, Block Design requires imitation, and the oral motor tasks also require imitation). One way to investigate this further would be to give a battery of tests including meaningless gesture imitation and non-gesture imitation, such as following an adult's sorting sequence (Alp, 1994).

Moving to the oral motor tasks, at 3 years language production is associated with concurrent complex oral movement skill even after other abilities – including earlier language production ability – are controlled for. This is the same finding as we made at 21 months, though it was not repeated at 4y. Again, these tasks require some degree of imitation though imitation in this task is propped up with explanation and commands. These tasks have minimal memory load (this subtask involves one movement at a time) and this association is not explained by associations with our repetition task (the PSRep, a task involving repetition of words and nonwords).

While again, it is possible that imitation itself is responsible for this association, the fact that this association is independent of both earlier language ability and concurrent repetition ability suggests that this is not due to language skill underling the oral motor task performance.

It seems more likely in both the case of the manual gesture and gross/fine motor contribution to language comprehension, and the oral motor contribution to language production, that it is the motor foundation of both of these tasks that explains additional variability in language skill. As hypothesised, this is likely due to either common neural mechanisms or a common underlying timing mechanism. While data from children with developmental coordination disorder (DCD) and DLD (Hill, 2001) strongly suggests a common neural mechanisms, other authors have put forward the case for common timing mechanisms in typical development (Esteve-Gibert & Prieto, 2014; Iverson & Thelen, 1999; Zelaznik & Goffman, 2010).

Most studies of typical variation in language ability do not control for manual and oral motor ability. However we and other groups have started to investigate these associations, both for children with language delay or impairment, and for the typically developing range of children (Hill, 2001; Krishnan et al., 2017; Krishnan et al., 2013; Krishnan et al., 2015; Leonard, Bedford, Pickles, Hill, & Team, 2015; Leonard & Hill, 2014). It seems that in our quest to understand the underlying differences in language development across the typical range, we should start to assume the inclusion of motor skill as standard in studies and batteries.

If motor abilities had not been tested in our study, a very different set of associations would have been found – we would have concluded that only nonverbal cognitive abilities and home stimulation contribute to language development in this age range. The results of other studies with similar design to ours, but without the inclusion of limb and oral motor skill tasks, should be viewed with caution, in the light of this.

Acknowledgements

We would like to thank families and children who have taken part.

References

Alcock, K. J. (1995). *Motor Dysphasia - a Comparative Study.* (DPhil Thesis), University of Oxford, Oxford, UK.

Alcock, K. J., & Krawczyk, K. (2006, Sep). *Correlates of individual differences in language development at 21 months.* Paper presented at the British Psychological Society, Developmental Section, Royal Holloway University College, Egham.

Alcock, K. J., & Krawczyk, K. (2008, July). *Names that are not words: older infants still associate non-linguistic sounds with pictures.* Paper presented at the International Congress for the Study of Child Language, Edinburgh.

Alcock, K. J., & Krawczyk, K. (2010). Individual differences in language development: Relationship with motor skill at 21 months. *Developmental Science, 13*(5), 677-691.

Alcock, K. J., Passingham, R. E., Watkins, K. E., & Vargha-Khadem, F. (2000). Oral dyspraxia in inherited speech and language impairment and acquired dysphasia. *Brain*

& Language, 75(1), 17-33.

Alp, I. E. (1994). Measuring the Size of Working Memory in Very Young Children: The Imitation Sorting Task. *International Journal of Behavioral Development, 17*(1), 125-141. doi:10.1177/016502549401700108

Aslin, R. N. (1989). Discrimination of frequency transitions by human infants. *Journal of the Acoustical Society of America, 86*(2), 582-590.

Bates, E. (1979). *The emergence of symbols - cognition and communication in infancy*. New York: Academic Press.

Bates, E. (1980). Vocal and gestural symbols at 13 months. *Merrill-Palmer Quarterly, 26*(4), 407-423.

Bates, E., & Dick, F. (2002). Language, gesture, and the developing brain. *Developmental Psychobiology, 40*(3), 293-310.

Bates, E., O'Connell, B., Vaid, J., & Sledge, P. (1986). Language and hand preference in early development. *Developmental Neuropsychology, 2*(1), 1-15.

Bates, E., Thal, D., Whitesell, K., & Fenson, L. (1989). Integrating language and gesture in infancy. *Developmental Psychology, 25*(6), 1004-1019.

Bayley, N. (1993). *Bayley scales of infant development* (2nd ed.). San Antonio, TX: Psychological Corporation.

Bergès, J., & Lézine, I. (1965). The imitation of gestures. *Clinics in developmental medicine, 18*, 1-122.

Bishop, D. V. M. (2002). Motor immaturity and specific speech and language impairment: Evidence for a common genetic basis. *American Journal of Medical Genetics, 114*(1), 56-63.

Bishop, D. V. M. (2003). *Test for reception of grammar : TROG-2*. London: Harcourt Assessment.

Botting, N., Riches, N., Gaynor, M., & Morgan, G. (2010). Gesture production and comprehension in children with specific language impairment. *British Journal of Developmental Psychology, 28*, 51-69.

Bricker, D., & Squires, J. (1989). Low cost system using parents to monitor the development of at-risk infants. *Journal of Early Intervention, 13*(1), 50-60.

Brumbach, A. C. D., & Goffman, L. (2014). Interaction of Language Processing and Motor Skill in Children With Specific Language Impairment. *Journal of Speech, Language, and Hearing Research, 57*(1), 158-171. doi:doi:10.1044/1092-4388(2013/12-0215)

Dale, P. S., Crain-Thoreson, C., & Robinson, N. M. (1995). Linguistic precocity and the development of reading: The role of extralinguistic factors. *Applied Psycholinguistics, 16*(2), 173-187. doi:10.1017/S0142716400007074

Davis, B. L., & MacNeilage, P. F. (1995). The articulatory basis of babbling. *Journal of Speech and Hearing Research, 38*(6), 1199-1211.

Dewey, D., & Wall, K. (1997). Praxis and memory deficits in language ‐ impaired children. *Developmental Neuropsychology, 13*(4), 507-512.

Elardo, R., & Bradley, R. H. (1981). The Home Observation for Measurement of the Environment (HOME) Scale: A review of research. *Developmental Review, 1*(2), 113-145.

Elliot, C. D., Smith, P., & McCullouch, K. (1997). *British Ability Scales: Second Edition*: NFER-Nelson.

Esteve-Gibert, N., & Prieto, P. (2014). Infants temporally coordinate gesture-speech combinations before they produce their first words. *Speech Communication, 57*, 301-316.

Fenson, L., Bates, E., Dale, P., Goodman, J., Reznick, J. S., & Thal, D. (2000). Measuring variability in early child language: don't shoot the messenger. *Child Development,*

71(2), 323-328.
Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D., & Pethick, S. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development, 59*(5).
Frankenburg, W. K., & Coons, C. E. (1986). Home Screening Questionnaire: its validity in assessing home environment. *Journal of Pediatrics, 108*(4), 624-626.
Ganger, J., & Brent, M. R. (2004). Reexamining the Vocabulary Spurt. *Developmental Psychology, 40*(4), 621-632.
Gathercole, S. E. (2006). Nonword repetition and word learning: The nature of the relationship. *Applied Psycholinguistics, 27*, 513–543.
Gernsbacher, M. A., Sauer, E. A., Geye, H. M., Schweigert, E. K., & Hill Goldsmith, H. (2008). Infant and toddler oral- and manual-motor skills predict later speech fluency in autism. *Journal of Child Psychology & Psychiatry & Allied Disciplines, 49*(1), 43-50.
Hamilton, A., Plunkett, K., & Schafer, G. (2000). Infant vocabulary development assessed with a British communicative development inventory. *Journal of Child Language, 27*(3), 689-705.
Hill, E. L. (1998). A dyspraxic deficit in specific language impairment and developmental coordination disorder? Evidence from hand and arm movements. *Developmental Medicine and Child Neurology, 40*(6), 388-395.
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*(2), 149-171.
Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian journal of statistics*, 65-70.

Iverson, J. M. (2010). Developing language in a developing body: the relationship between motor development and language development. *Journal of Child Language, 37*(02), 229-261. doi:doi:10.1017/S0305000909990432

Iverson, J. M., & Braddock, B. A. (2011). Gesture and motor skill in relation to language in children with language impairment. *Journal of Speech, Language, and Hearing Research, 54*(1), 72-86.

Iverson, J. M., & Thelen, E. (1999). Hand, mouth and brain: The dynamic emergence of speech and gesture. *Journal of Consciousness Studies, 6*(11-12), 19-40.

Krishnan, S., Alcock, K. J., Carey, D., Bergström, L., Karmiloff-Smith, A., & Dick, F. (2017). Fractionating nonword repetition: The contributions of short-term memory and oromotor praxis are different. *PLOS One, 12*(7), e0178356.

Krishnan, S., Alcock, K. J., Mercure, E., Leech, R., Barker, E., Karmiloff-Smith, A., & Dick, F. (2013). Articulating Novel Words: Children's Oromotor Skills Predict Nonword Repetition Abilities. *Journal of Speech, Language, and Hearing Research, 56*(6), 1800-1812.

Krishnan, S., Bergström, L., Alcock, K. J., Dick, F., & Karmiloff-Smith, A. (2015). Williams syndrome: A surprising deficit in oromotor praxis in a population with proficient language production. *Neuropsychologia, 67*, 82-90.

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

LeBarton, E. S., & Iverson, J. M. (2016). Associations between gross motor and communicative development in at-risk infants. *Infant Behavior and Development, 44*, 59-67. doi:https://doi.org/10.1016/j.infbeh.2016.05.003

Leonard, H. C., Bedford, R., Pickles, A., Hill, E. L., & Team, B. (2015). Predicting the rate of language development from early motor skills in at-risk infants who develop autism spectrum disorder. *Research in Autism Spectrum Disorders, 13*, 15-24.

Leonard, H. C., & Hill, E. L. (2014). Review: the impact of motor development on typical and atypical social cognition and language: a systematic review. *Child and Adolescent Mental Health, 19*(3), 163-170.

Lewis, V., Boucher, J., & Psychological Corporation. (1997). *The test of pretend play*. London: The Psychological Corporation: Harcourt Brace.

MacWhinney, B. (2000). *The CHILDES project: tools for analyzing talk* (3rd ed.). Mahwah, N.J.: Lawrence Erlbaum.

Nip, I. S. B., Green, J. R., & Marx, D. B. (2011). The co-emergence of cognition, language, and speech motor control in early development: A longitudinal correlation study. *Journal of Communication Disorders, 44*(2), 149-160.

O'toole, C., & Chiat, S. (2006). Symbolic functioning and language development in children with Down syndrome. *International Journal of Language & Communication Disorders, 41*(2), 155-171.

Office of National Statistics. (2004). Indices of Deprivation for Super Output Areas. Retrieved from http://www.neighbourhood.statistics.gov.uk/dissemination/

Ojemann, G. A. (1984). Common cortical and thalamic mechanisms for language and motor functions. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology, 246*(6), R901-R903.

Renfrew, C. E. (2001). *Bus story test : a test of narrative speech*. Bicester: Speechmark.

Rescorla, L. A. (2002). Language and reading outcomes to age 9 in late-talking toddlers. *Journal of Speech Language and Hearing Research, 45*(2), 360-371.

Rescorla, L. A. (2011). Late talkers: Do good predictors of outcome exist? *Developmental Disabilities Research Reviews, 17*(2), 141-150.

Roy, P., & Chiat, S. (2004). A prosodically controlled word and nonword repetition task for

2-to 4-year-olds: Evidence from typically developing children. *Journal of Speech Language and Hearing Research, 47*(1), 223-234.

Roy, P., & Chiat, S. (2005). *Symbolic comprehension assessment.* .

Sanjeevan, T., & Mainela-Arnold, E. (2017). Procedural Motor Learning in Children With Specific Language Impairment. *Journal of Speech, Language, and Hearing Research, 60*(11), 3259-3269. doi:doi:10.1044/2017_JSLHR-L-16-0457

Sanjeevan, T., Rosenbaum, D. A., Miller, C., van Hell, J. G., Weiss, D. J., & Mainela-Arnold, E. (2015). Motor Issues in Specific Language Impairment: a Window into the Underlying Impairment. *Current Developmental Disorders Reports, 2*(3), 228-236. doi:10.1007/s40474-015-0051-9

Saudino, K. J., Dale, P. S., Oliver, B., Petrill, S. A., Richardson, V., Rutter, M., . . . Plomin, R. (1998). The validity of parent-based assessment of the cognitive abilities of 2-year-olds. *British Journal of Developmental Psychology, 16*(3), 349-363.

Scarborough, H. S. (1990). Index of Productive Syntax. *Applied Psycholinguistics, 11*(1), 1-22.

Schonhaut, L., Armijo, I., Schönstedt, M., Alvarez, J., & Cordero, M. (2013). Validity of the Ages and Stages Questionnaires in Term and Preterm Infants. *Pediatrics, 131*(5), e1468-e1474. doi:10.1542/peds.2012-3313

Skeat, J., Wake, M., Reilly, S., Eadie, P., Bretherton, L., Bavin, E. L., & Ukoumunne, O. C. (2010). Predictors of early precocious talking: A prospective population study. *Journal of Child Language, 37*(5), 1109-1121. doi:10.1017/S030500090999016X

Slavin, S. (2007). PsyScript (version 2.1)[software].

Squires, J., Potter, L., & Bricker, D. (1995). *The ASQ user's guide for the Ages & Stages Questionnaires: A parent-completed, child-monitoring system*: Brookes.

Steeve, R. W., & Moore, C. A. (2009). Mandibular Motor Control During the Early

Development of Speech and Nonspeech Behaviors. *Journal of Speech Language and Hearing Research, 52*(6), 1530-1554. doi:10.1044/1092-4388(2009/08-0020)

Thal, D. J., & Tobias, S. (1994). Relationships between language and gesture in normally developing and late-talking toddlers. *Journal of Speech and Hearing Research, 37(1)*(1), 157-170.

Volterra, V., Caselli, M. C., Capirci, O., & Pizzuto, E. (2005). Gesture and the emergence and development of language. *Beyond nature-nurture: Essays in honor of Elizabeth Bates*, 3-40.

West, K. L., Leezenbaum, N. B., Northrup, J. B., & Iverson, J. M. (2019). The Relation Between Walking and Language in Infant Siblings of Children With Autism Spectrum Disorder. *Child Development, 90*(3), e356-e372. doi:10.1111/cdev.12980

Wray, C., Norbury, C., & Alcock, K. J. (2016). Gestural abilities of children with specific language impairment. *International Journal of Language and Communication Disorders, 51*(2), 174-182. doi:10.1111/1460-6984.12196

Zelaznik, H. N., & Goffman, L. (2010). Generalized motor abilities and timing behavior in children with specific language impairment. *Journal of Speech, Language, and Hearing Research, 53*(2), 383-393.

Zimmerman, I., Steiner, V., & Pond, R. (2003). *Preschool Language Scale-3 UK Edition (PLS-3 UK)*. London: The Psychological Corporation.

Table 1

Time 1 – 21 months – skills measured and tests used

Skill measured	Assessment used	Format of assessment	N
Language production	Oxford Communicative Development Inventory (CDI) - Production	Parent checklist[1]	121
Language comprehension	Oxford CDI – Comprehension	Parent checklist[1]	121
Gross motor skills	Bayley Scales of Motor Development; or questionnaire	Standardised RA-administered test[2] or parent checklist[3]	30; 102
Fine motor skills	Bayley Scales of Motor Development; or questionnaire	Standardised RA-administered test[2] or parent checklist[3]	30; 102
Meaningful gesture	Lab based test of symbolic gesture and gesture memory; or questionnaire	RA- administered test or parent checklist[4]	30; 103
Meaningless gesture	Lab based test of meaningless gesture	RA-administered test[5]	30
Oral motor skill	Lab based test of imitation and prop-based oral movements	RA-administered test[6]	60

[1] Hamilton et al. (2000)
[2] Bayley (1993)
[3] Based on Bricker and Squires (1989)
[4] Lab created based on Bates et al. (1989), or based on Fenson et al. (1994)
[5] Lab created
[6] Lab created based on Alcock (1995)

Cognitive ability	Bayley Scales of Mental Development, Test of Pretend Play and joint attention task; or parent questionnaire (PARCA).	Standardised RA-administered test[2,7] or parent checklist[8]	29; 91

[7] Lewis et al. (1997)
[8] Based on Saudino et al. (1998)

Table 2

Descriptives for 3 year tests. Maximum possible indicates the highest score that a child can obtain on that test, where this is meaningful (i.e. not where a child is unlikely to obtain the maximum). In all cases high scores represent better performance.

	N	Mean	Std. Dev.	Min	Max	Max possible
PLS Expressive 3y	89	11.72	5.93	0	27	-
PLS Auditory 3y	89	16.13	4.74	0	26	-
PLS combined 3y	89	27.85	9.76	0	53	-
Oral Motor Control 3y	39	12.56	3.89	3	18	20
Complex Oral Motor Control 3y	39	7.21	2.32	1	11	12
Gesture Sequencing 3y	18	11.56	3.68	3	15	15
Meaningless Gesture 3y	32	14.00	2.44	8	18	20
HSQ 3y	83	63.49	7.79	47	83	84
Symbolic Comprehension 3y	28	12.46	4.57	1	18	18
Block Design 3y	34	3.79	2.77	1	12	-
PSRep score 3y	42	26.69	5.58	13	36	36
Motor questionnaire	84	30.46	5.31	15	38	50

Table 3

Language and cognitive scores at 21 months, correlation (Pearson's r) with 3y language

Measures at 21 months:		CDI prodn	CDI comp	PLS Expressive	PLS Auditory	PLS combined	PARCA	Bayley Mental	TOPP	JA
PLS Expressive 3y	**r**	.48** †	.40**†	.48 (.02)	.326	.46 (.03)	.49 (.02)	.22	.34	-.04
	N	84	84	23	23	23	23	20	23	20
PLS Auditory 3y	**r**	.41**†	.31 (.004)	.56 (.005)	.17	.67**†	.45 (.03)	.04	.31	.13
	N	84	84	23	23	23	23	20	23	20
PLS combined 3y	**r**	.49**†	.40**†	.54 (.01)	.27	.61 (.002)†	.50 (.02)	.18	.35	.03
	N	84	84	23	23	23	23	20	23	20

Motor and SES scores 21 mo and language 3 years, Pearson's correlation

Measures at 21 months:		Oral motor	Gesture naming	Meaningless Gesture	Gesture sequences	Bayley Motor	IMD
PLS Expressive 3y	**r**	.38 (.02)	.31	.45	-.16	.39	.02
	N	40	20	16	20	16	73
PLS Auditory 3y	**r**	.38 (.02)	.23	.41	-.22	.17	.04
	N	40	20	16	20	16	73
PLS combined 3y	**r**	.43 (.01)	.32	.54 (.03)	-.21	.37	.03
	N	40	20	16	20	16	73

** $p < .001$; Blank - $p > .05$; Other p values in brackets. † Remains significant after correction for multiple comparisons.

Table 4

Cognitive, motor, and home stimulation scores at 3 years, correlations (Pearson's r) with 3 year language

		Oral Motor Control	Gesture Sequence	Meaningless Gesture	Motor questionnaire	HSQ	Symbolic Comprehension	Block Design 3y	PSRep 3y
PLS Expr.	**r**	.50 (.001)†	.40	.45 (.01)	.29 (.01)	.24 (.03)	.56 (.002)†	.02	.39 (.01)
	N	39	18	32	77	82	27	73	42
PLS Auditory	**r**	.29	.46	.71**†	0.46**†	.38**†	.51 (.01)	.04	.34 (.03)
	N	39	18	32	83	82	27	73	42
PLS Comb.	**r**	.46 (.003)†	.48 (.04)	.62**†	.41**†	.34 (.002)†	.57 (.002)†	.03	.39 (.01)
	N	39	18	32	84	82	27	73	42

** p < .001; Blank - p > .05.; Other p values in brackets. † Remains significant after correction for multiple comparisons.

Table 5

Results of regression analysis examining the relationship between 21 month language, cognitive and motor variables, 3 year cognitive and motor variables, and 3 year language

	Variable	B	SE B	β (p)
PLS Expressive 3y – Motor correlates – Model 1				
Step 1 (R^2 = .28 p = .004)	CDI Production 21 mo	.02	.01	.31
	CDI Comprehension 21 mo	.02	.01	.27
Step 2 (ΔR^2 = .09, p = .04)	CDI Production 21 mo	.02	.01	.25
	PARCA score 21 mo	.01	.01	.16
	Oral Motor Control 3y	.49	.23	.34 (.04)
PLS Expressive 3y – Symbolic Comprehension as a predictor – Model 2				
Step 1 (R^2 = .55, p <.001)	CDI Production 21 mo	.04	.02	.61 (.02)
	CDI Comprehension 21 mo	.01	.02	.13
Step 2 (ΔR^2 = .15, p = .001)	CDI Production 21 mo	.02	.02	.31
	CDI Comprehension 21 mo	.02	.02	.30
	Symbolic Comprehension 3y	.52	.19	.40 (.01)
PLS Auditory Comprehension 3y – Motor predictors – Model 3				
Step 1 (R^2 = .54 p < .001)	CDI Production 21 mo	.04	.01	.74 (<.001)
Step 2 (ΔR^2 = .19 p = .001)	CDI Production 21 mo	.02	.01	.37 (.01)
	Meaningless Gesture 3y	.84	.24	.43 (.002)
	Gross/fine motor questionnaire 3y	.23	.10	.29 (.03)
PLS Total 3y – Motor predictors – Model 5				

Step 1 ($R^2 = .29$ $p = .005$)	CDI Comprehension 21 mo	.08	.02	.54 (.003)
Step 2 ($\Delta R^2 = .40$ $p < .001$)	CDI Comprehension 21 mo	.05	.02	.36 (.014)
	Oral Motor Control 3y	1.57	.60	.46 (.017)
	Meaningless Gesture 3y	.85	.58	.24
	Gross/fine motor questionnaire 3y	.07	.22	.05
PLS Total 3y – Symbolic Comprehension as a predictor – Model 6				
Step 1 ($R^2 = .26$ $p = .009$)	CDI Comprehension 21 mo	.06	.02	.51 (.009)
Step 2 ($\Delta R^2 = .28$ $p = .007$)	CDI Comprehension 21 mo	.05	.02	.39 (.02)
	Symbolic Comprehension 3y	1.13	.32	.53 (.002)
	HSQ 3y	.37	.44	.13

Blank = $p > .05$, other p values in brackets.

Table 6

Descriptives for 4 year tests. Maximum possible indicates the highest score that a child can obtain on that test, where this is meaningful.

	N	Mean	Std. Deviation	Minimum	Maximum	Maximum possible
TROG (standard score)	67	104.49	15.55	79	145	
Type-Token Ratio (Bus Story)	65	.63	.10	.42	1.000	
VOCD	54	38.52	12.85	11.05	74.81	
MLU	66	5.46	1.61	1.50	10.21	
IPSYN	66	42.24	9.97	4	59	
Complex Oral Motor Control	66	11.35	1.78	6	14	14
Oral Motor Control combinations	65	25.98	5.25	7	34	38
Meaningless Gesture	65	41.69	6.28	26	58	104
Block Design	67	9.15	3.11	1	15	
Auditory Discrimination	57	67.11	58.36	33.33	300.00	300

Table 7

Language, motor and cognitive scores at 21 months, correlation (Pearson's r) with 4y language

Measures at 21 months		CDI prodn	CDI comp	PLS Expressive	PLS Auditory	PARCA	Oral motor	Gesture score
TROG 4y	**r**	.27 (.03)	.39 (.002)†	.23	.28 (.03)	.05	.34	.28 (.03)
	N	64	64	61	61	34	14	61
TTR (Bus Story) 4y	**r**	-.10	-.03	-.16	-.07	-.10	.52	-.14
	N	62	62	59	59	33	12	59
VOCD 4y	**r**	.05	-.03	-.03	.09	-.11	.65 (.03)	.03
	N	52	52	51	51	26	11	51
MLU 4y	**r**	.16	.01	.38 (.003)	.24	-.00	.36	.36 (.005)
	N	63	63	60	60	33	12	60
IPSYN 4y	**r**	.02	-.12	.27 (.03)	.33 (.009)	.15	-.13	.34 (.008)
	N	63	63	60	60	33	12	60

Blank - p > .05; Other p values in brackets. †Remains significant after correction for multiple comparisons

Table 8

Motor and cognitive scores at 3y, correlation (Pearson's r) with 4y language

Measures at 3y:		Oral motor 3y	Meaningless Gesture 3y	Motor q'airre 3y	HSQ 3y	Symbolic Comprehension 3y	Block Design 3y	PSRep score 3y
TROG 4y	**r**	.02	.05	.13	.31** †	.31	.16	.20
	N	28	25	58	57	19	24	30
TTR (Bus Story) 4y	**r**	-.29	.01	-.06	-.17	.32	-.32	-.19
	N	29	25	56	55	18	21	30
VOCD 4y	**r**	-.18	.16	-.20	-.12	.28	-.38	.15
	N	26	23	49	48	17	16	26
MLU 4y	**r**	.41 (.03)	.27	-.23	.075	.50 (.03)	.21	.28
	N	29	26	57	56	19	21	31
IPSYN 4y	**r**	.23	.38	-.18	-.01	.71 (.001) †	.09	.36 (.05)
	N	29	26	57	56	19	21	31

** p < .001; Blank - p > .05.

Other p values in brackets. †Remains significant after correction for multiple comparisons

Table 9

Motor and cognitive scores at 4y, correlation (Pearson's r) with 4y language

		Complex Oral Motor Control 4y	Oral Motor Control Combinations 4y	Gesture score 4y	Block Design 4y	Auditory Discrimination 4y
TROG 4y	**r**	.11	.28 (.03)	.28 (.03)	.22	.20
	N	62	62	62	66	54
TTR (Bus Story) 4y	**r**	-.29 (.02)	-.20	.02	-.12	.05
	N	64	63	63	61	50
VOCD 4y	**r**	.12	.23	.09	.07	.06
	N	54	53	53	53	44
MLU 4y	**r**	.32 (.01)	.21	.01	.14	-.06
	N	65	64	64	62	51
IPSYN 4y	**r**	.31 (.01)	.37 (.003) †	.04	.08	.06
	N	65	64	64	62	51

Blank - p > .05; Other p values in brackets. †Remains significant after correction for multiple comparisons

Table 10

Results of regression analysis examining the relationship between 21 month and 3 year language, cognitive and motor variables, and 4 year language outcomes

	Variable	B	SE B	β (p)
4y receptive language (TROG) predicted by 21 month language and HSQ - Model 1				
Step 1 (R^2 = .10 p = .02)	CDI Comprehension	.07	.03	.32 (.02)
Step 2 (ΔR^2 = .07 p = .04)	CDI Comprehension	.06	.03	.28 (.03)
	HSQ 3y	1.16	.64	.25 (.04)
4y expressive language (IPSYN) predicted by 3y Symbolic Comprehension and 4y Oral Motor Control – Model 2				
Step 1 (R^2 = .52, p = .001)	Symbolic Comprehension 3y	1.67	.40	.72 (.001)
Step 2 (ΔR^2 = .05 n.s.)	Symbolic Comprehension 3y	1.93	.44	.83 (.001)
	Oral Motor Control Combinations 4y	-.44	.34	-.25

Blank = p > .05, other p values in bracket