Developmental Science

Developmental Science (2016), pp 1–15 DOI: 10.1111/desc.12487

PAPER

Mothers speak differently to infants at-risk for dyslexia

Marina Kalashnikova,[1] Usha Goswami[2] and Denis Burnham[1]

1. The MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Australia
2. Centre for Neuroscience in Education, University of Cambridge, UK

Abstract

Dyslexia is a neurodevelopmental disorder manifested in deficits in reading and spelling skills that is consistently associated with difficulties in phonological processing. Dyslexia is genetically transmitted, but its manifestation in a particular individual is thought to depend on the interaction of epigenetic and environmental factors. We adopt a novel interactional perspective on early linguistic environment and dyslexia by simultaneously studying two pre-existing factors, one maternal and one infant, that may contribute to these interactions; and two behaviours, one maternal and one infant, to index the effect of these factors. The maternal factor *is whether mothers are themselves dyslexic or not (with/without dyslexia) and the* infant factor *is whether infants are at-/not-at family risk for dyslexia (due to their mother* or *father being dyslexic). The maternal behaviour is mothers' infant-directed speech (IDS), which typically involves vowel hyperarticulation, thought to benefit speech perception and language acquisition. The infant behaviour is auditory perception measured by infant sensitivity to amplitude envelope rise time, which has been found to be reduced in dyslexic children. Here, at-risk infants showed significantly poorer acoustic sensitivity than not-at-risk infants and mothers only hyperarticulated vowels to infants who were not at-risk for dyslexia. Mothers' own dyslexia status had no effect on IDS quality. Parental speech input is thus affected by infant risk status, with likely consequences for later linguistic development.*

Research highlights

- Infants at family risk for dyslexia already show impaired auditory discrimination of rise time at 7 and 10 months of age.
- Mothers speaking to infants at-risk for dyslexia do not hyperarticulate vowels when producing infant-directed speech.
- Mothers' own dyslexia status did not impact on the qualities (pitch, affect, and vowel articulation) of infant-directed speech.
- Mothers adjust their infant-directed speech to infants at-risk for dyslexia, so at-risk infants experience altered early linguistic input in the first years of life.

Introduction

Dyslexia affects approximately 10% of children worldwide. It manifests as severe deficits in reading and spelling skills, and is independent of a child's general intelligence and educational opportunities (Snowling, 2000). A family history of dyslexia increases its risk; 35 to 60% of infants born to a dyslexic parent (mother or father) also develop dyslexia later in childhood (Gallagher, Frith & Snowling, 2000; Lyytinen, Aro, Eklund, Erskine, Guttorm *et al*., 2004; Pennington & Lefly, 2001; van der Leij, van Bergen, van Zuijen, de Jong, Maurits *et al*., 2013). Nevertheless, although only *some children* at familial risk for dyslexia develop later reading deficits, there is evidence that *all infants* at familial risk for dyslexia may share an underlying auditory processing deficit (Leppänen, Hämäläinen, Salminen, Eklund, Guttorm *et al*., 2010). In this regard, it appears that epigenetic and environmental factors and/or their interaction may affect whether dyslexia is manifested in any particular individual (Pennington, 2006). Here we assess the developmental effects of such factors by studying the early linguistic environment of infants at-risk (AR) and not at-risk (NAR) for dyslexia (the 'infant factor' here). We take an interactional approach by examining both the mother's own dyslexia status (the 'mother factor'

Address for correspondence: Marina Kalashnikova, The MARCS Institute for Brain, Behaviour and Development, Western Sydney University, Penrith, Australia, 2751; e-mail: m.kalashnikova@westernsydney.edu.au

here) and infant auditory sensitivity (the infant behaviour variable). Specifically, we compare mother-infant dyads in which the infant is AR or NAR for dyslexia and for the AR infants, whether the mother is dyslexic or not, and measure (a) parameters of the mother's infant-directed speech (IDS), in particular the degree of vowel hyperarticulation, and (b) infants' sensitivity to amplitude envelope rise time (hereafter 'rise time').

Rise time refers to the time taken for any sound envelope to reach its highest amplitude (peak energy). Amplitude envelope rise time perception is impaired in children with dyslexia across various languages (Goswami, 2015). Accordingly, we focus on rise time as the infant auditory sensitivity index here. Sensitivity to rise time is critical for speech processing, as rise times at different temporal rates in the speech envelope function as auditory edges, resetting the endogenous neuronal oscillations that encode the spectro-temporal properties of the speech signal (Gross, Hoogenboom, Thut, Schyns, Panzeri *et al.*, 2013). Although the sensory or neural precursors of dyslexia are still debated (Goswami, 2015), studies across languages show that children and adults with dyslexia exhibit reduced sensitivity to the slow changes in the amplitude modulations of the speech signal that dominate the amplitude envelope (Goswami, 2011; Hämäläinen, Salminen & Leppänen, 2012). Dyslexic children learning English, French, Spanish, Chinese, Dutch, Hungarian, and Finnish all show reduced sensitivity to variations in rise time. Impaired rise time discrimination is associated with difficulties in perceiving speech rhythm (Goswami, Huss, Mead, Fosker & Verney, 2013), speech prosodic structure, phonology, and reading (Goswami, Gerson & Astruc, 2010).

Prior family risk studies demonstrate that auditory rise time processing is a significant correlate of familial risk for dyslexia, with reduced performance in auditory sensitivity shown by at-risk children who may or may not manifest reading difficulties later in childhood (Hakvoort, van der Leij, Maurits, Maassen & van Zuijen, 2015; Plakas, van Zuijen, van Leeuwen, Thomson & van der Leij, 2013). However, rise time perception has yet to be assessed in *infants* at familial risk for dyslexia. This is surprising, as rise time perception is related to sensitivity to speech rhythm, and sensitivity to speech rhythm and prosodic structure are known to be important universally for early language acquisition (Mehler, Jusczyk, Lambertz, Halsted, Bertoncini *et al.*, 1988). In the current study, infants completed a rise time discrimination task as a behavioural measure of their auditory processing abilities at 7 and 10 months. AR infants were expected to show higher discrimination thresholds than NAR infants.

While rise time has not been investigated in infants at-risk for dyslexia, other early deficits in auditory processing have been documented. For instance, there are hemispheric differences between AR and NAR infants' processing of linguistic and acoustic features, consonantal contrasts and changes in pitch (Guttorm, Leppänen, Hämäläinen, Eklund & Lyytinen, 2010; Leppänen, Richardson, Phko, Eklund, Guttorm *et al.*, 2002; Richardson, Leppänen, Leiwo & Lyytinen, 2003; van Zuijen, Plakas, Maassen, Maurits & van der Leij, 2013), which are associated with later language ability and verbal memory. That auditory difficulties in AR infants are present irrespective of the later developmental trajectory is intriguing with respect to Pennington's hypothesis that not all AR infants develop dyslexia later in childhood due to particular interactions of epigenetic and environmental factors in each individual case (Pennington, 2006). Accordingly, here we assess the genetic/epigenetic contribution to the linguistic environment by mother status (dyslexic or not) and infant status (AR or NAR for dyslexia) indexed by the acoustic, affective, and phonetic features of their mothers' speech.

Compared to adult-directed speech (ADS), infant-directed speech (IDS) has simplified grammatical and semantic content (Soderstrom, Blossom, Foygel & Morgan, 2008). Acoustic analyses also reveal slower tempo, exaggerated pitch, higher affect (Fernald & Kuhl, 1987; Kuhl, Andruski, Chistovich, Chistovich, Kozhevnikova *et al.*, 1997), and 'vowel hyperarticulation', expansion of the phonetic vowel space (Kuhl *et al.*, 1997), which is thought to fulfil a didactic function (Liu, Kuhl & Tsao, 2003). In order to assess the effect of the mother and the infant factor on IDS, three of these parameters were measured here – pitch, affect, and vowel hyperarticulation.

Pitch height in maternal speech changes over age, increasing from birth to 3 and 6 months, and then decreasing to 9 and 12 months (Kitamura & Burnham, 2003). Similarly with affect, ratings of low-pass filtered IDS samples show that affective content in mothers' speech is modified according to infants' age: speech is rated as predominantly 'comforting' to 3-month-olds, 'approving' to 6-month-olds, and 'directive' to 9-month-olds (Kitamura & Burnham, 2003). Most interestingly, these affect ratings align with infant behaviour; more comforting, approving, and directive speech is preferred specifically by 3-, 6-, and 9-month-old infants, respectively (Kitamura & Lam, 2009). These data suggest that mothers give infants what they 'want' in terms of vocal affect. Other data suggest that this is also the case for vowel hyperarticulation, to which we now turn.

Vowel hyperarticulation involves an expansion of phonetic space, resulting in easier perceptual differentiation and better speech intelligibility (Bradlow, Torretta & Pisoni, 1996). Vowel hyperarticulation is indexed by plotting first and second formant (F1, F2) values of the three corner vowels, /i/, /u/, and /a/, in F1/F2 space, calculating the area of the triangle connecting their centroid values, and comparing these triangle areas across speech registers (in this case IDS and ADS). Using this method, Kuhl *et al*. (1997) showed that vowel triangle areas of English, Russian, and Swedish mothers were significantly larger when they spoke to their 5-month-old infants (IDS) than to another adult (ADS). Subsequent studies suggest that vowel hyperarticulation serves a didactic function, as the degree to which mothers hyperarticulate vowels in IDS is positively related to infants' linguistic abilities such as discrimination of consonant contrasts in their language (Liu *et al*., 2003) and early word recognition (Song, Demuth & Morgan, 2010). In addition, the presence of vowel hyperarticulation appears to be independent of pitch and affect variation, and is not confined to IDS; rather, it appears to occur in response to the audience's linguistic potential. For example, vowel hyperarticulation occurs in speech to foreigners (Uther, Knoll & Burnham, 2007) where concomitant positive affect is absent, and in speech to humanoid machines (Burnham, Joeffry & Rice, 2010). Conversely, speech directed to cats and dogs is high in affect but does not have hyperarticulated vowels (Burnham, Kitamura & Vollmer-Conna, 2002), although vowels *are* hyperarticulated in speech directed to pets with perceived linguistic potential, namely parrots (Xu, Burnham, Kitamura & Vollmer-Conna, 2013). This suggests that speakers (probably unconsciously) selectively modify their speech to adapt to the needs of the audience; they enhance their vowel articulation depending on whether they perceive that their audience has the capacity for language acquisition.

Here we will test whether exogenous mothers' behaviour, vowel hyperarticulation, varies according to the endogenous infant factor, infants' auditory ability. There is some evidence that such adaptation of IDS does occur in the case of hearing impairment. A case study of a mother speaking to her two infant sons, one with normal and one with impaired hearing, found *reduced* vowel hyperarticulation in the mothers' IDS to the hearing impaired son, while the pitch and affect in her speech to the two infants did not differ (Lam & Kitamura, 2010). This could have been due to the mother's conscious or unconscious decision not to speak as clearly to the hearing impaired son, and/or to her unconscious response to differential signals that her two infant sons provided. A subsequent study assessed vowel hyperarticulation when a hearing impairment in the infant was simulated. Mothers and their 6- to 7-month-old infants were located in different rooms, and interacted via live feed on a double video set-up with video monitors in each room (Lam & Kitamura, 2012). 'Hearing impairment' simulations were created by reducing the amplitude of the mother's speech to the infant to half the normal level or by turning it off entirely. Mothers hyperarticulated their vowels significantly less when their infant heard their speech at half volume, and did not hyperarticulate at all in the no-sound condition. Importantly, these modifications occurred regardless of whether the mothers were blind to the experimental manipulation or not. This suggests that the critical mechanism is behavioural feedback from the infant audience, an infant factor, with this feedback determining the nature of the IDS, rather than adults' explicit knowledge about the linguistic potential or competence of their infant. These modifications to maternal linguistic behaviours in response to infants' feedback can occur during the course of a single communicative interaction (Lam & Kitamura, 2012; Smith & Trainor, 2008), and can also be a manifestation of the development over time of parental competence in assessing the cognitive and linguistic abilities and the needs of their infant. Through repetitive interactions during the first months of their infants' life, parents acquire the knowledge about how to interpret and assign meaning to the communicative behaviours of their infant, which allows them to attune their own responses to the infants' changing developmental needs (Papoušek, 2007; Parsons, Young, Murray, Stein & Kringelbach, 2010). Accordingly, in the case of IDS, it has been speculated that babies actually control the nature of the speech directed to them, so that it is consistent with their intrinsic abilities and needs, be they perceptual, neurological, or linguistic (Englund & Behne, 2006).

Nevertheless, there are also clear examples of mother factors in the literature. For instance, mothers with postnatal depression produce IDS that differs in emotional and affective qualities from IDS produced by healthy mothers (Kaplan, Bachorowski, Smoski & Hudenko, 2002). In the case of dyads in which the infant is at-risk for dyslexia, the presence of other mother factors is also possible. That is, infants can be at-risk for dyslexia because only their father is dyslexic (i.e. their mother has typical reading and language skills) or because only their mother is dyslexic, or both. If the mother is dyslexic, then this mother factor (manifested in the particular linguistic deficits) could influence the inherent qualities of her speech to her infant and even to others and/or decrease her sensitivity to her infant's linguistic needs and the communicative feedback from her infant. Research investigating the effects of maternal dyslexia on mother–infant interactions has been scarce and has produced mixed findings. For instance, it has been demonstrated that when addressing their at-risk infants, mothers who are themselves dyslexic produce language that is comparable in its structural qualities to that produced by non-dyslexic mothers (Scarborough & Fichtelberg, 1993). However, mothers with dyslexia have also been shown to produce speech that is less symbolic in nature, and such speech has been shown to be a significant negative predictor of infants' later vocabulary skills (Lyytinen, Eklund & Lyytinen, 2003).

The present study assessed the infant factor by comparing two mother-infant dyad groups: one comprising infants who were at familial risk for dyslexia by virtue of having at least one dyslexic parent (AR group), and the other infants who were not at familial risk for any learning disorder (NAR group). The composition of the AR group allowed assessment of the mother factor of dyslexia; this group comprised two mother-status subgroups: mothers who were dyslexic and mothers who had typical language and reading skills (but whose infants were at-risk for dyslexia because of a history of dyslexia on their fathers' side). Given that IDS qualities modulate as a function of infant age and linguistic proficiency (Kitamura & Burnham, 2003), mothers' speech was recorded when addressing their infant at both 9 and 11 months, and for comparison, when addressing another adult.

The first and second predictions concern the infant factor (NAR vs. AR). The first prediction was that there should, as is the case for older children diagnosed with dyslexia, be compromised *infant behaviour*, rise time discrimination, in the AR compared to the NAR infants. The second prediction concerns any subsequent effect of the infant factor on *mother's behaviour*; it was predicted that there should be vowel hyperarticulation to NAR infants, but not to AR infants. However, since IDS to infants with a hearing impairment differs only on the vowel hyperarticulation dimension (Lam & Kitamura, 2010, 2012), for the other two dependent variables, pitch and affect, IDS in all groups was predicted to exhibit equally heightened pitch and affect. The third prediction concerns the mother factor. In addition to, and not mutually exclusive from, the second prediction, if the mother factor (dyslexia status) impacts upon the quality of maternal speech, IDS produced by mothers without dyslexia should exhibit vowel hyperarticulation, whereas IDS to AR infants produced by dyslexic mothers should not. This prediction will be tested by measuring vowel hyperarticulation by dyslexic mothers to AR infants compared to non-dyslexic mothers' IDS to AR infants. The final prediction concerns the relationship between infant and mother behaviour: if deficits in auditory processing endogenous to the infant result in less hyperarticulation in the mother's speech, then a significant relationship between our measures of infants' auditory rise time perception abilities and mothers' vowel hyperarticulation would be expected.

Method

Participants

Thirty-six mother-infant dyads participated: 18 infants were in the not-at-risk group (NAR, 11 female) and 18 in the at-risk group (AR, 11 female). All infants were born full-term, had no reported health complications, and had normal hearing. IDS sessions were recorded at the infant ages of 9 (M = 40.29 weeks, SD = 4.7) and 11 months (M = 48.96, SD = 4.7). The rise time discrimination task was completed in three additional experimental sessions at the infant ages of 7 (M = 32.13, SD = 4.94) and 10 months (M = 44.57, SD = 4.87). Four infants (three AR and one NAR) were reported to have exposure to a second language at home, but this exposure was slight, and English was the primary language environment for all infants. All infants were selected from a larger sample of the Seeds of Literacy longitudinal project based on their family history for dyslexia and mothers' availability to take part in all the experimental sessions.

Mothers and fathers of all infants were screened to check self-reports of dyslexia. Screening included two reading tasks: word and non-word reading (Test of Word Reading Efficiency; Torgesen, Wagner & Rashotte, 1999), digit span (Wechsler Individual Achievement Test II, WIAT; Breaux, 2010), oral reading (WIAT), spelling (WIAT), and rapid picture naming (Woodcock-Johnson III; Schrank & McGrew, 2001). In addition, parents completed a measure of non-verbal IQ (Matrix Reasoning and Block Design sub-tests from the Wechsler Adult Intelligence Scale; Wechsler, 2014). Infants were assigned to the at-risk group if at least one of their parents obtained scores that were 1.5 SD or more below the standardized mean in (a) one of the reading tests and (b) three or more of the remaining screening tests, and (c) both parents obtained average non-verbal IQ scores. Infants with at least one dyslexic parent (N = 18) were placed in the AR group and another 18 infants were in the NAR group. Within the AR group, nine mothers did not have a diagnosis of dyslexia (i.e. their infant was placed in the AR group because of a history of dyslexia on the father's side), and nine mothers had a diagnosis of dyslexia. Table 1 presents the screening scores from the language and general IQ tests for all mothers. Non-dyslexic mothers in each group did not differ in their performance on any language or non-verbal IQ

Table 1 *Mothers' performance on the screening battery*

	NAR	AR non-dyslexic mother	AR dyslexic mother	$F(2,23)$
WIAT III[1] – Word reading subtest[a]	110.89 (5.1)	102.44 (9.9)	85.1 (16.7)	19.020**
WIAT III[1] – Non-word reading subtest[a]	108.78 (10.4)	95.33 (13.9)	72.89 (19.8)	19.535**
TOWRE[2] – Sight word efficiency[a]	113.33 (11.7)	103.67 (14.3)	96.78 (13.7)	5.309*
TOWRE[2] – Phonemic decoding efficiency[a]	113.78 (10.8)	104.9 (15.8)	80.22 (13.5)	20.601**
WIAT III[1] – Spelling subtest[a]	115.33 (7.4)	105.01 (10.8)	83.44 (15.1)	27.432**
WIAT III[1] – Oral Reading Fluency[a]	107.39 (6.8)	101.89 (10.4)	89.33 (22.1)	5.815*
WIAT III[1] – Oral Reading Accuracy[a]	110.51 (10.1)	100.67 (14.3)	78.67 (29.1)	9.894**
WIAT III[1] – Oral Reading Rate	107.5 (6.9)	102.78 (9.1)	100.11 (29.9)	.689
Woodcock-Johnson – RAN	109.72 (10.4)	104.67 (16.1)	97.67 (14.9)	2.554
WAIS[3] – Digit span[a]	10.83 (2.8)	9.33 (2.4)	8.01 (2.9)	3.337^
Adult Reading History Questionnaire[a]	.21 (.1)	.23 (.1)	.45 (.1)	18.531**
WAIS[3] – Non-Verbal IQ subtests[a]	12.51 (1.9)	11.56 (2.1)	10.17 (1.5)	4.705*[4]

[a]NA = AR non-dyslexic mother > AR dyslexic mother; $**p < .001$; $*p < .02$; $^p < .05$ [1]Wechsler Individual Achievement Test; [2]Test of Word Reading Efficiency; [3]Wechsler Adult Intelligence Scale. [4]Only parents whose non-verbal IQ score was not below 0.5 *SD* from the standardized mean were included in the study.

measures, whereas the dyslexic mothers obtained significantly lower scores than non-dyslexic mothers on all measures except for rapid automated naming.

All mothers (M age = 32.89 years, SD = 4.9) were native speakers of Australian English. Mothers' median education level was a higher university level degree (Masters), and it did not differ between the two groups, Mann-Whitney U = 60.5, p = .17. Nevertheless, dyslexic mothers in the AR group had lower educational levels than mothers in the other two subgroups, Kruskal-Wallis test, χ^2 (N = 36, 2) = 8.965, p = .011. The socioeconomic status (SES) of the participating families was assessed based on the average household weekly income level corresponding to the postcode of their residence (Australian Bureau of Statistics). There were no significant differences in SES levels between the families in the NAR and AR groups, $t(34) = -1.256$, p = .218, with all families falling within the middle or higher middle-class range.

Rise time discrimination

Materials and apparatus

The stimuli consisted of a set of 20 pure sine tones (500 Hz, 800 ms in duration). The duration to maximum rise time of the tones was manipulated systematically, increasing from 15 ms (steady state portion 735 ms, fall time 50 ms) to 300 ms (steady state portion 450 ms, fall time 50 ms) in 15 ms intervals. The visual stimuli consisted of two images of coloured checkerboards. Visual stimuli were presented on three computer monitors, with the checkerboards appearing on the left and right monitor, and an attention-getter stimulus in the centre. Audio stimuli were presented over loudspeakers located behind the right and left monitors.

Procedure

The rise time task is an infant version of a two alternative forced-choice (2AFC) adaptive threshold procedure (Goswami, Fosker, Huss, Mead & Szücs, 2011). Infants were seated on their parent's lap facing the three monitors in a sound-attenuated infant testing booth. After infants fixated the centre monitor, the images of a checkerboard appeared on the right and left screens. Infants' fixations to the monitor on one side produced a repeating auditory stimulus (15 ms, 15 ms, 15 ms, 15 ms, etc.), while fixations to the monitor on the other side produced an alternating stimulus (15 ms, 300 ms, 15 ms, 300 ms, etc.). Side of presentation was counterbalanced across participants. Greater (55%) fixation to the alternating stimulus side for two trials resulted in a step down, e.g. 15, 270, 15, 270, . . ., and less than 55% to a step back up (i.e. a reversal occurred every time that the steps changed direction). Testing continued for a maximum of 25 trials, which incorporated a control for side preference in which the repeating and alternating sides were reversed for the final three trials of the task (see Figure 1 for a graphical representation of the rise time task). The average rise time difference between alternating stimuli recorded for the three last step reversals by each infant in the task was used as the rise time discrimination threshold for analyses.

Infant-directed speech

Mothers and infants participated in IDS interactions alone in a child-friendly laboratory room. Mothers sat facing their infants who sat in a high chair. Four video cameras, one mounted in each corner of the room, allowed for monitoring and video recording of the

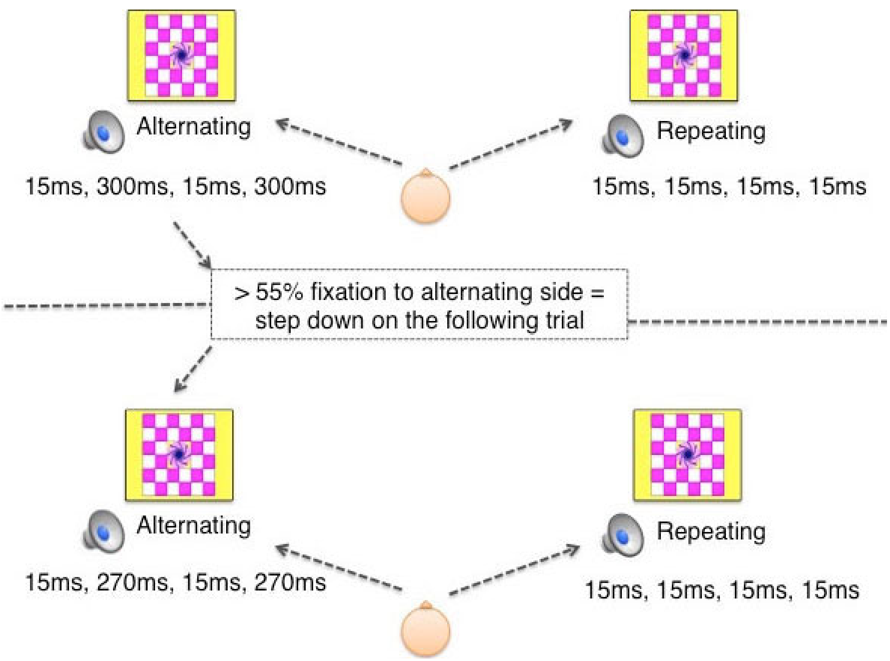

Figure 1 *Staircase 2AFC preferential looking paradigm.*

sessions. The mother wore a head-mounted microphone (AudioTechnica AT892), connected to Adobe Audition CS6 software via an audio input/output device (MOTU Ultralite MK3). The experimenter monitored the video and audio for each session from an adjoining room. For the ADS session, each mother interacted with a female experimenter in the same room in which the IDS sessions took place, and the same apparatus was used. The infants were not present in the room during the ADS sessions.

For analyses, the recordings of each IDS and ADS session were separated into segments defined as a period of mother's speech not interrupted by vocalizations of the infant, or noises from the environment. Praat software (Boersma & Weenink, 2005) was used to segment and excise the audio segments. A total of 221 segments were extracted for IDS 9 months, 190 for IDS 11 months, and 181 for ADS. The resulting segments ranged from 6 to 27 seconds in duration. There were no significant differences between the number of segments or the duration of segments collected in the two groups (all *ps* >.1).

From these segments measures of pitch height were extracted for each mother and the segments were also used for affect ratings (see below). Next, the target words *sheep*, *shoe*, and *shark* were located and excised from the segments, and the target corner vowels /i/, /u/, /a/ extracted. Only the corner vowels from these three target words were used for analyses in order to reduce potential effects from differential consonant co-articulation and to ensure that all mothers had similar opportunities in the IDS and ADS sessions to produce the target words. Praat scripts were used to measure the values for the fundamental frequency and first and second formants for each vowel.

The formant values used were the mean value in Hz from the 40% and 80% points of each vowel's duration (Munhall, MacDonald, Byrne & Johnsrude, 2009). Given the logarithmic nature of pitch perception, all F0 values were converted into perceptual units (Mels) using the following formula:

$$\text{Semitone} = 12\text{LOG}_2(\text{Max F0}/\text{Min F0})$$

Mean F1 and F2 values were calculated for each target vowel for each mother and each register (ADS, IDS at 9 months, IDS at 11 months). This information was used to calculate the vowel triangle areas using the following formula where F1/a/ refers to the average value in Hz of the first formant for the vowel /a/, F2/i/ refers to the average value in Hz of the second formant for the vowel /i/, and so forth:

$$\text{ABS } 1/2 \times [(\text{F1/a/} \times (\text{F2/i/} - \text{F2/u/}) + \text{F1/i/} \times (\text{F2/u/} - \text{F2/a/}) + \text{F1/u/} \times (\text{F2/a/} - \text{F2/i/})]$$

This yielded three triangle area values for each mother (ADS, IDS at 9 months, and IDS at 11 months).

Affect ratings

Stimuli

Two segments (ranging from 10 to 20 seconds each) from each of the IDS recordings and ADS recording for each of the 36 mothers were selected. The first segment was extracted from the start of each recording, and the second from 3 minutes into the recording or the closest possible time point to 3 minutes that contained no environmental noise. The selected samples were low-pass filtered at a frequency of 400 Hz using the Fast Fourier Transform filter in the Cool Edit Pro software (Petelin & Petelin, 2003). The segments for each speaker in each register (2 segments × 3 registers × 36 mothers = 216 total segments) were concatenated into a single audio string each separated by 5 seconds of silence resulting in a total of 108 strings (three strings for each mother).

Participants and procedure

In order to make the length of the task manageable, stimulus strings were randomly assigned to blocks of 36 items that were administered in a between-subjects design, each block containing IDS (9 months and 11 months) and ADS strings from the AR and NAR groups. These blocks were administered to adult raters (undergraduate students), so that 15 raters completed each block of low-pass filtered speech strings.

Affect data analyses

The low-pass filtered strings were presented via headphones on a computer using DMDX software (Foster & Foster, 2003). Participants were instructed to listen to each string and rate it on five 7-point Likert scales: affective content, the speaker's communicative intention to express affection, to encourage attention, and to comfort or soothe, or to direct behaviour. Ratings for each item for each scale were averaged across raters and entered into a principal components analysis, which yielded two components for each register, 'expressing affect' and 'directing attention' (Table 2). Averaged factor scores for the 'expressing affect' component were used in the main analyses.

Results

Infant factor

The effect of the infant factor (NAR vs. AR) was assessed on the infants' behaviour measured by the rise time discrimination task and the mothers' behaviour indexed by the measures of pitch, rated affect, and vowel articulation in IDS.

Rise time discrimination

In order to account for missing cases resulting from the longitudinal design (cases for 6 NAR and 8 AR infants were missing for the 7-months test, and from 10 NAR and 9 AR infants in the 10-months test), a general linear mixed model analysis was conducted for rise time discrimination scores. A single model was constructed and comprised two fixed factors (infant status group: NAR, AR and age: 7 months, 10 months) and an interaction (status group by age), a random intercept for participants, and the rise time perception threshold as the dependent variable. The estimates for fixed effects and interaction in the resulting model (AIC = 416.544) are presented in Table 3. As can be seen, the model yielded significant main effects of group and age, and a significant age by group interaction. Figure 2 shows that this interaction was due to AR infants' higher auditory thresholds than NAR infants at 10 months, but not at 7 months. We also checked the average rise time threshold for 10-month-old AR infants whose mothers were either themselves dyslexic or not. The mean scores did not differ, $F < 1$ (M mothers without

Table 2 *Principal components analysis for the expressing affect and directing attention components of IDS and ADS*

	ADS		IDS 9 months		IDS 11 months	
	Express affection	Direct attention	Express affection	Direct attention	Express affection	Direct attention
Emotion	0.914	0.268	0.824	0.217	0.956	0.197
Affection	0.913	0.34	0.91	0.311	0.485	0.766
Attention	0.385	0.872	0.546	0.765	0.352	0.834
Comfort	0.964	−0.001	0.918	0.019	0.314	0.794
Direct behaviour	0.038	0.962	0.033	0.964	0.018	0.929
Eigenvalues	2.82	1.37	2.74	1.88	2.65	1.66
Explained variance	56.31%	27.45%	54.96%	37.49%	52.98%	33.17%

Table 3 *Estimates of fixed effects (group: AR, NAR; age: 7 mos, 10 mos) and interaction (group by age) for the general linear mixed model analyses of rise time discrimination thresholds by NAR and AR infants at 7 and 10 months of age*

	Estimate (*SE*)	*df*	*t*-value
Group	−68.38 (24.74)	15.389	−2.764 (p = .014)
Age	−51.878 (23.63)	24.605	−2.196 (p = .038)
Group × Age	33.568 (15.99)	18.985	2.769 (p = .012)

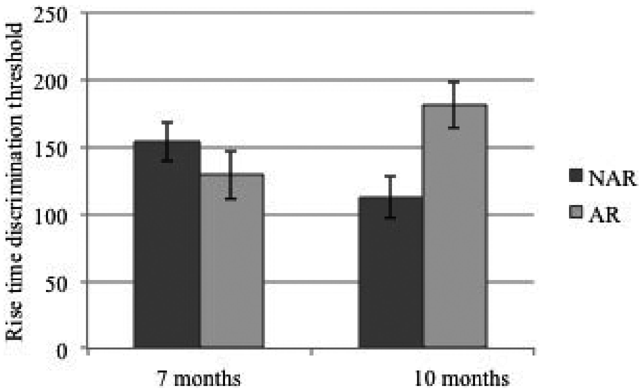

Figure 2 *Rise time discrimination threshold scores for NAR and AR infants at 7 and 10 months of age.*

dyslexia = 197.69, *SE* = 30.07; *M* mothers with dyslexia = 172.12, *SE* = 21.26).

Infant-directed speech

In order to account for mothers' individual differences in speech production in IDS and ADS, hyper-speech scores (IDS/ADS) were computed for the three dependent measures, mean pitch height of utterances, rated affect factor scores, and vowel triangle area based on /i/, /u/, /a/ F1 and F2 values for each mother-infant dyad. A hyper-speech score above 1 denotes the presence of heightened pitch, affect, or vowel space in IDS in comparison to ADS, a hyper-score of 1 denotes no difference between IDS and ADS, and a hyper-score score below 1 denotes hypo-speech for IDS compared to ADS. Two sets of Analysis of Variance (ANOVA) were conducted. First, hyper-speech scores for pitch, affect, and vowel area were compared *between the two infant-factor groups* (NAR, AR), and over age (9, 11 months) to assess whether IDS modifications occurred when mothers addressed infants who were at-risk compared to not at-risk for dyslexia. Second, the hyper-speech scores for pitch, affect, and vowel area were compared *between the two mother-factor groups* within the AR group (AR mother without dyslexia, AR mother with dyslexia) to assess whether mothers' dyslexia status resulted in IDS modifications. In addition to these ANOVAs, one-sample *t*-tests were conducted comparing appropriate hyper-scores with unity (1) to assess whether hyper-speech was present or absent in IDS for each of the three dependent variables.

Infant factor analyses: hyper-speech scores for pitch, affect, and vowel area

Three ANOVAs of hyper-speech scores (for pitch, affect, and vowel area) were conducted to determine any differences in hyper-speech. Each ANOVA had one two-level between-subjects factor (group: NAR, AR), and one two-level within-subjects factor (age of infant when IDS was recorded: 9 months, 11 months). Then, one-sample *t*-tests were conducted to compare hyper-speech scores to unity. Bonferroni corrections were used to adjust alpha levels (α = .025 for each *t*-test). Hyper-pitch, hyper-affect, and hyper-vowel area scores for the NAR and AR groups are shown in Figure 3 along with the results of *t*-tests against unity, and the raw vowel triangle areas for speech to 9-month-olds, 11-month-olds and adults in Figure 4.

Hyper-pitch

Analysis of the degree of hyper-pitch in the NAR and AR groups showed no main effect of age at which IDS was recorded, $F < 1$ (*M* 9 mos = 1.066, *SE* = .004; *M* 11 mos = 1.065, *SE* = .004), no effect of NAR vs. AR group, $F < 1$ (*M* NAR = 1.06, *SE* = .005; *M* AR = 1.07, *SE* = .005), and no interaction, $F < 1$. So, mothers in the NAR and AR groups exhibited equivalent degrees of hyper-pitch to both 9- and 11-month-olds, with no difference in the degree of heightened pitch to NAR and AR infants. For the *t*-tests, as there was no effect of age, hyper-pitch scores for IDS at 9 months and IDS at 11 months were averaged for each dyad. Hyper-pitch scores were significantly greater than 1 for both the NAR and the AR groups ($t(17)$ = 10.683, $p < .001$ and $t(17)$ = 14.777, $p < .001$, respectively). Thus, together the ANOVA and *t*-tests show that there was statistically significant hyper-pitch to infants in both the NAR and AR groups, and this was statistically equivalent across the two groups.

Hyper-affect

Analysis of hyper-affect in the NAR and AR groups also showed no differences between age of IDS, $F < 1$ (*M* 9 mos = 9.251, *SE* = 2.014; *M* 11 mos = 9.127, *SE* = 2.201), between the NAR and AR groups, $F < 1$ (*M* NAR = 9.82, *SE* = 2.01; *M* AR = 8.56, *SE* = 2.20),

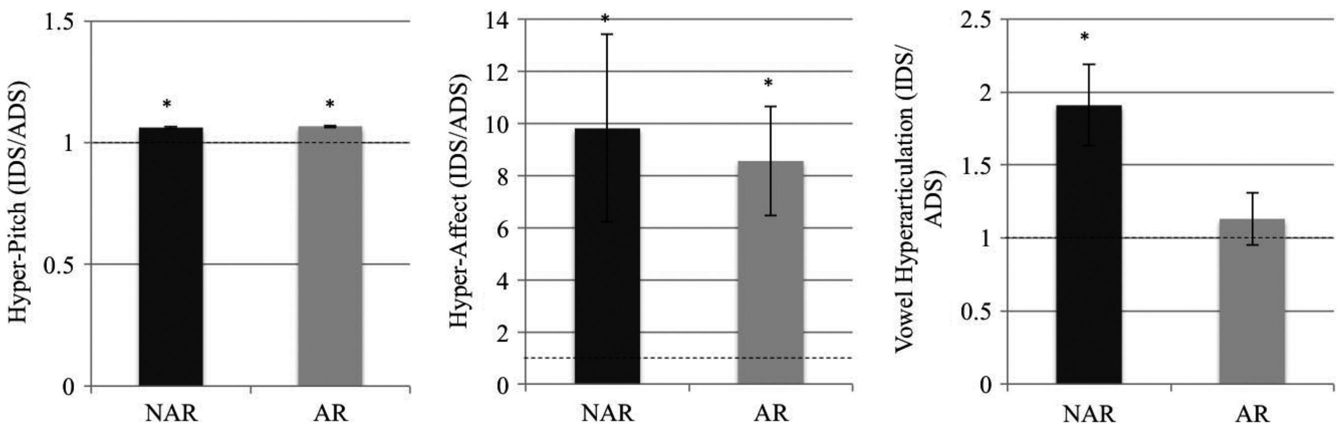

Figure 3 *Indices of hyper-pitch, hyper-affect, and vowel hyperarticulation produced by mothers in the NAR and AR groups averaged for IDS at 9 and 11 months (the dotted lines represent the test value of 1;* *p < .025; *error bars represent SEM).*

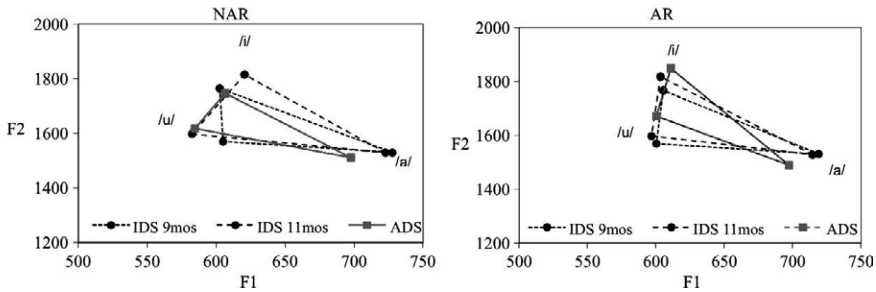

Figure 4 *Vowel triangles produced by mothers when speaking to their NAR and AR infants at 9 and 11 months of age and to another adult.*

or for their interaction, $F < 1$. Again, as there was no effect of age, hyper-affect *t*-tests were conducted on scores averaged across 9 and 11 months. Hyper-affect scores were significantly greater than 1 for both the NAR and the AR groups ($t(17) = 2.454$, $p = .025$, $t(17) = 3.609$, $p = .002$, respectively). So, as for pitch, there was hyper-affect to both NAR and AR infants, and the degree of hyper-affect did not differ as a function of infants' risk status.

Hyper-vowel area

Consonant with the hyper-pitch and hyper-affect results, there were no differences in hyper-vowel area between the two infant ages, $F < 1$ (M 9 mos = 1.632, $SE = .273$; M 11 mos = 1.409, $SE = .178$), and no interaction of age with NAR vs. AR groups, $F < 1$. However, in contrast to hyper-pitch and hyper-affect, there *was* significantly more vowel hyperarticulation in the NAR than the AR group, $F(1, 34) = 5.504$, $p = .025$, $\eta^2 = .139$ (M NAR = 1.91, $SE = .27$; M AR = 1.13, $SE = .18$); mothers with NAR infants hyperarticulated vowels significantly more than did mothers with AR infants. As there was no age effect of, hyper-vowel area scores at 9 and 11 months were averaged for the *t*-tests. Hyper-vowel area scores were greater than 1 for the NAR group ($t(17) = 3.264$, $p = .005$) but not the AR group ($t(17) = .734$, $p = .473$). Thus, there was hyper-vowel articulation *present* in speech to NAR, but *absent* to AR infants, and, the *degree* of hyper-vowel articulation was significantly greater to the NAR group.

Mother factor: hyper scores for pitch, affect, and vowel areas

In order to assess the effects of the mother factor, mothers' own dyslexia status, on IDS qualities beyond the effects of infants' family risk status, hyper-speech scores for pitch, affect, and vowel areas were compared between the two AR mother status groups: AR mothers with dyslexia and AR mothers without dyslexia (see Figure 5 for hyper scores and Figure 6 for vowel triangles for these two groups). Two (group: AR mothers with dyslexia, AR mothers without dyslexia) by two (age: IDS at 9 months, IDS at 11 months) ANOVAs were conducted for each dependent variable followed by

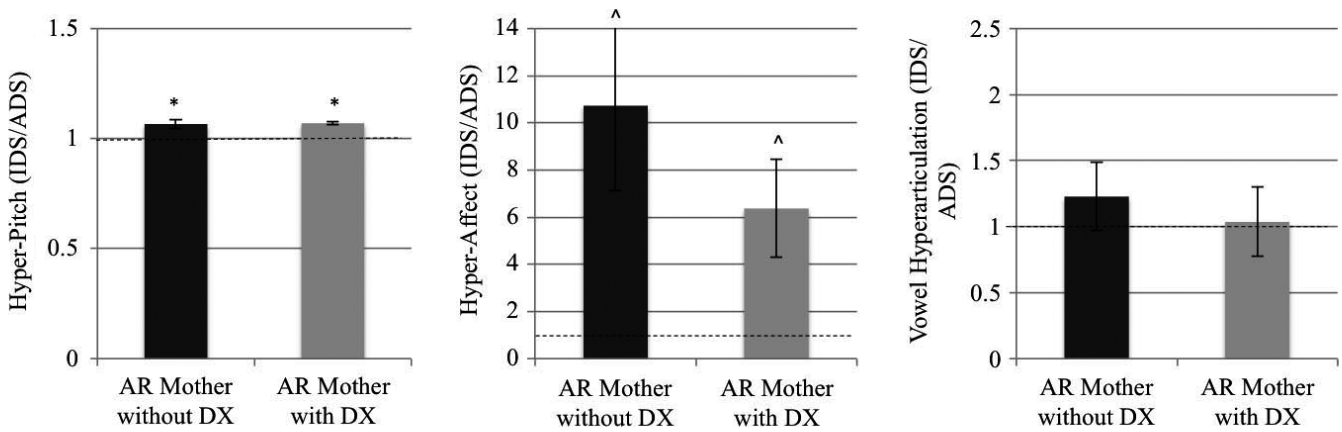

Figure 5 *Indices of hyper-pitch, hyper-affect, and vowel hyperarticulation produced in the two mother-status groups (AR mothers with and without dyslexia) averaged for IDS at 9 and 11 months (the dotted lines represent the test value of 1; *p < .025; ^p < .05; error bars represent SEM).*

t-tests against unity (1) to test for the presence or absence of significant hyper-speech.

Hyper-pitch

Analyses of hyper-pitch in the two AR mother status groups showed no main effect of infant age, $F < 1$ (M 9 mos = 1.068, SE = .005; M 11 mos = 1.068, SE = .006), of mother status group, $F < 1$ (M without dyslexia = 1.066, SE = .007; M with dyslexia = 1.070, SE = .007), or their interaction, $F < 1$. Given that there were no age differences, hyper-scores were averaged over age for the *t*-tests. In the AR group of mothers without dyslexia, hyper-pitch scores were greater than 1, $t(8) = 9.067$, $p < .001$, and this was also the case for mothers with dyslexia, $t(8) = 11.654$, $p < .001$. So, dyslexic and non-dyslexic mothers showed hyper-pitch in IDS and the degree of hyper-pitch was statistically equivalent regardless of dyslexia status.

Hyper-affect

Comparisons of hyper-affect between the two groups also showed no differences between IDS age, $F < 1$ (M 9 mos = 8.524, SE = 1.973; M 11 mos = 8.592, SE = 2.315), between the mother status groups, $F < 1$ (M without dyslexia = 10.747, SE = 2.953; M with dyslexia = 6.369, SE = 2.953), or their interaction, $F < 1$. *T*-test analyses (averaged for IDS at 9 months and 11 months) showed that for mothers without and with dyslexia, hyper-affect scores marginally differed from 1 ($t(8) = 2.692$, $p = .027$ and $t(8) = 2.579$, $p = .033$, respectively). It is possible that the analyses against unity failed to reach statistical significance due to the small sample sizes in the two sub-groups, but crucially, the degree of hyper-affect was high (see Figure 5) and did not vary as a function of mothers' own dyslexia status.

Hyper-vowel area

Contrary to the results for pitch and affect, for hyper-vowel area there was a significant effect of the age at which IDS was recorded, $F(1, 16) = 4.830$, $p = .043$, $\eta^2 = .232$ (M 9 mos = 1.355, SE = .261; M 11 mos = .909, SE = .141). There was, however, no main effect of mother status group, $F < 1$ (M without dyslexia = 1.227, SE = .260, M with dyslexia = 1.036, SE = .260), and no age by mother status interaction, $F < 1$. Therefore, regardless of their own dyslexia status, IDS produced by mothers speaking to their infants at-risk for dyslexia was significantly less hyperarticulated at 11 months than at 9 months. Furthermore, vowel hyperarticulation scores (averaged across the two IDS ages) produced by mothers without, $t(8) = .882$, $p = .403$, and with dyslexia, $t(8) = .138$, $p = .894$, did not differ from 1.

Together, these findings show that mothers in the AR group produced heightened pitch and affect in IDS irrespective of whether they themselves were dyslexic. Neither maternal AR group, dyslexic or not, produced vowel hyperarticulation. Interestingly, the AR mothers produced a significantly greater degree of vowel hyperarticulation to their infants at 9 months compared to later, when the infants were 11 months. This occurred whether the mothers were themselves dyslexic or not.

Relationship between the infant and mother behaviour: rise time and hyper-speech

Correlations between infants' auditory perception scores and their mothers' degree of vowel hyperarticulation are

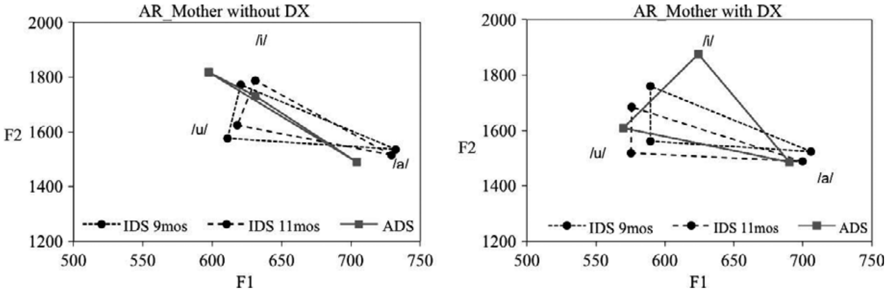

Figure 6 *Vowel triangles produced by mothers with and without dyslexia when speaking to their AR infants at 9 and 11 months of age and to another adult.*

Table 4 *Correlation analyses between infants' rise time discrimination thresholds at 7 and 10 months and the hyperarticulation index in their mothers' speech at infants' ages of 9 and 11 months* (*N* = 26, **p* < .05)

	Hyperarticulation 9 mos	Hyperarticulation 11 mos
Rise time 7 mos	.031	−.104
Rise time 10 mos	−.493*	.149

shown in Table 4. There was a significant correlation between infants' rise time discrimination threshold at 10 months and mothers' hyperarticulation index in IDS at 9 months, $r(17) = -.493$, $p = .044$. This negative relationship indicates that infants who develop more advanced auditory processing abilities are exposed to a greater degree of hyperarticulation in their mothers' speech.

Discussion

This is the first infant study to investigate how epigenetic and environmental factors and their interaction might affect whether dyslexia is manifested in any particular individual, by simultaneously studying infant status (NAR, AR) and mother status (dyslexic, not dyslexic) factors using dependent variables specific to infants (their auditory rise time discrimination) and mothers (the acoustic, affective, and phonetic qualities of IDS). We found support for an infant factor in both the infant- and the mother-specific dependent variables; infants' rise time discrimination was significantly better in the NAR group than in the AR group, and while there were no differences in hyper-pitch and hyper-affect, mothers' vowel hyperarticulation was significantly greater to the NAR infant group than to the AR infant group. Further, there was a weak correlation between these two variables; the degree to which their mothers hyperarticulated vowels at 9 months was related to infants' rise time discrimination at 10 months. These results are strengthened by the hyper-speech scores; there was vowel hyperarticulation in the NAR but not the AR group; scores were around unity for mothers of AR infants (no hyper-vowel articulation) but the ratios were around two (around twice the vowel triangle area in IDS than ADS) for mothers of NAR infants. This suggests that there is a key role for the infant factor of being at-risk vs. not-at-risk for dyslexia in the early language-learning environment. This is apparent in differences in infants' behaviour, rise time discrimination, and in a related fashion (and possibly even as a result of these auditory differences), differences in mothers' behaviour, vowel hyperarticulation. Thus, while the causal direction cannot be determined here, infants' intrinsic auditory abilities may play a significant role in determining their early linguistic environment for language learning.

Accordingly, infants at familial risk for developing dyslexia already have compromised auditory sensitivity to amplitude rise time in the first year of life (irrespective of whether they will later be diagnosed with dyslexia or not). This could result in differences in the way in which speech is delivered to infants, and also in the way the available speech input is processed by the infants, with potentially life-long consequences (Goswami *et al.*, 2011, 2013; Hämäläinen *et al.*, 2012). For example, these deficits in auditory processing could impair infant use of speech rhythm and prosodic cues for encoding and parsing the speech signal, and also early neural entrainment to the temporal modulation patterns in speech (Goswami, 2011, 2015).

With respect to the etymology of the mothers' differences in vowel hyperarticulation, as neither pitch height nor rated affect in mothers' speech differed between mothers of AR and NAR infants, it appears that mothers were not *consciously* adapting their speech to their infants' abilities. Further, the lack of vowel hyperarticulation to AR infants was not due to dyslexia-related characteristics of the mothers. Analysis of IDS to the AR babies by mothers who were themselves dyslexic vs. those who were not dyslexic showed no overall differences in pitch height, rated affect or vowel hyperarticulation. Indeed, it appears that mothers' experience in talking to AR infants may affect their vowel hyperarticulation irrespective of their own dyslexia status. The analyses focusing solely on mothers who were speaking to AR infants showed that all mothers *decreased* their degree of vowel hyperarticulation from when their infants were 9 months to when they were 11 months of age. Critically, this age-related modification in vowel hyperarticulation was equivalent for mothers who were or were not themselves dyslexic. This suggests that the more mothers speak to their AR infants, the more they may pick up on cues from the infant (via rise time differences, and/or other sources) that result in decreased vowel hyperarticulation. Vowel production has not previously been studied in this population, but our results align with previous research by Scarborough and Fichtelberg (1993) who also found no effects of maternal dyslexia status on structural aspects of IDS. Specifically, our findings indicate that the linguistic deficits associated with dyslexia in the mother do not impact the qualities of speech that she produces when addressing her infant or her sensitivity to her infant's communicative cues, but that the cues from the infant may result in her changing the nature of her speech.

Our results show that the early linguistic environment experienced by infants at familial risk for dyslexia is different from that of infants who are not at-risk. This may consist of a combination of endogenous (quality of auditory processing) and exogenous (quality of speech input, at least with respect to vowel hyperarticulation) factors. In our study, this is evidenced by the weak correlation between infants' rise time thresholds and the degree to which their mothers hyperarticulated vowels in IDS. As only one of the four correlations computed was significant, this could be a chance finding. However, additional analyses for the pitch and affect factors found no significant correlations with infants' performance in the rise time discrimination task.[1] This suggests that vowel hyperarticulation and not other aspects of IDS could be related to auditory perception in the infant. The exact nature of this relationship and its source requires further investigation. Pending such future inquiry, this result supports an epigenetic explanation: family risk for dyslexia is expressed, at least in part, via compromised auditory processing ability, which in turn may modify the early linguistic environment provided by the mother. AR infants in our study appear to exert similar influences on maternal IDS to those observed for hearing impaired infants (Lam & Kitamura, 2010). It is quite possible that mothers of AR infants, while not hyperarticulating vowels, may instead emphasize other acoustic cues required or 'requested' by their infants. While no other cues were measured in this study, possibilities include regularization of speech rhythm patterns (Leong, Kalashnikova, Burnham & Goswami, 2014) or language-specific intonational exaggeration (Igarashi, Nishikawa, Tanaka & Mazuka, 2013). Further studies are required in which such measures are added to those in the current study. For example, further fine-grained analyses may reveal that the vowel hyperarticulation differences between AR and NAR groups are compensated by concurrent variations in other IDS features that are more suited to (or requested by) the AR infants' level or mode of processing. Alternatively, there may be differences in the onset of mothers' hyperarticulation to NAR vs. AR infants. The most logical expression of this would be a delay in the onset of hyperarticulation to AR infants, but the reduction in vowel hyperarticulation from 9 to 11 months suggests the opposite; AR mothers may begin by hyperarticulating vowels and then abandon this to replace it by some, as yet unknown, other behaviour more suited to their infant's sensory level or mode of processing. In either event, further studies with younger and older infants including a wider range of dependent variables will be useful.

One possible compensatory behaviour by mothers is suggested by recent research. While previous research has demonstrated that IDS facilitates linguistic and multimodal learning processes (Ma, Golinkoff, Houston & Hirsh-Pasek, 2011; Kubicek, De Boisferon, Dupierrix, Pascalis, Lœvenbruck *et al.*, 2014; Thiessen, Hill & Saffran, 2005), and that maternal vowel hyperarticulation specifically relates to better speech perception and word recognition skills in the infant (Liu *et al.*, 2003; Song *et al.*, 2010), more recent evidence has suggested that increased variability in speech sound articulation makes IDS a *less* discriminable form of speech input (Martin, Schatz, Versteegh, Miyazawa, Mazuka *et al.*, 2015; McMurray, Kovack-Lesh, Goodwin & McEchron, 2013). Hence, it could be suggested that mothers speaking to AR infants may not hyperarticulate vowels *precisely because* they are implicitly producing IDS that is more similar to ADS to *facilitate* the task of speech discrimination for their young infants. Therefore, future

[1] No significant correlations were found between rise time discrimination at 7 months or 10 months, and hyper-pitch or hyper-affect scores at 9 months or 11 months (all *ps* > .2).

research should investigate individual developmental patterns in NAR and AR infants to assess the impact (positive or negative) of vowel hyperarticulation and other qualities of maternal speech on infants' language development.

In conclusion, mothers and infants appear to tune into each other's perceptual and cognitive skills, producing complex and dynamic communicative interactions within the IDS microcosm (Hasson, Chazanfar, Galantucci, Garrod & Keysers, 2012); and this results in different language learning environments for infants who are at family risk for dyslexia. The results may also extend beyond the microcosm involving infants at family risk for dyslexia; future specification of the auditory, visual, emotional, or other cues involved in early interactions may well afford sensitive environmental enrichment programmes and provide insights into how infants at-risk for cognitive or sensory impairments *and* typically developing infants may contribute to their own developmental pathways. This intriguing possibility awaits further investigation.

Finally, it is important to note that the AR infants in this study do not have a definite dyslexia status, and prior research suggests that only 30 to 65% of them will go on to be diagnosed as dyslexic (Gallagher *et al*., 2000; van der Leij *et al*., 2013). Nevertheless, their rise time processing abilities and the nature of their mothers' IDS *already* differentiate them from infants who do not have a genetic predisposition for dyslexia. As noted earlier, individuals who are at genetic risk for dyslexia but are not later diagnosed as dyslexic are not entirely unimpaired (Pennington, 2006). The emergence of dyslexia is complex and multifaceted and, over and above genetic familial risk, is determined by factors such as the language and reading abilities of *each* parent, the home-literacy environment, and the linguistic abilities of the child. Our findings add a new (risk or protective) factor: mothers speak differently to infants at-risk for dyslexia.

Acknowledgements

This research was supported by Australian Research Council grant DP110105123, 'The Seeds of Literacy', to the third and second authors. We would like to thank all the parents and infants for their valuable time and interest in this research.

References

Australian Bureau of Statistics. http://www.abs.gov.au.

Boersma, P., & Weenink, D. (2005). Praat: Doing phonetics by computer (Version 4.3. 14). Computer program: http://www.praat.org.

Bradlow, A.R., Torretta, G.M., & Pisoni, D.B. (1996). Intelligibility of normal speech I: Global and fine-grained acoustic-phonetic talker characteristics. *Speech Communication*, **20**, 255–272.

Breaux, K.C. (2010). *Wechsler Individual Achievement Test* (3rd edn.). San Antonio, TX: Pearson.

Burnham, D., Joeffry, S., & Rice, L. (2010). *Computer and human-directed speech before and after correction*. Paper presented at the ASSTA meeting, Melbourne, Australia.

Burnham, D., Kitamura, C., & Vollmer-Conna, U. (2002). What's new pussycat? On talking to babies and animals. *Science*, **296** (5572), 1435.

Englund, K., & Behne, D. (2006). Changes in infant directed speech in the first six months. *Infant and Child Development*, **15**, 139–160.

Fernald, A., & Kuhl, P. (1987). Acoustic determinants of infant preference for motherese speech. *Infant Behaviour and Development*, **10**, 279–293.

Foster, K.I., & Foster, J.C. (2003). DMDX: a window display program with millisecond accuracy. *Behavioural Research Methods, Instruments & Computers*, **35**, 116–124.

Gallagher, A., Frith, U., & Snowling, M.J. (2000). Precursors of literacy delay among children at genetic risk of dyslexia. *Journal of Child Psychology and Psychiatry*, **41** (2), 203–213.

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, **15** (1), 3–10.

Goswami, U. (2015). Sensory theories of developmental dyslexia: three challenges for research. *Nature Reviews Neuroscience*, **16**, 43–54.

Goswami, U., Fosker, T., Huss, M., Mead, N., & Szücs, D. (2011). Rise time and formant transition duration in the discrimination of speech sounds: the Ba–Wa distinction in developmental dyslexia. *Developmental Science*, **14** (1), 34–43.

Goswami, U., Gerson, D., & Astruc, L. (2010). Amplitude envelope perception, phonology and prosodic sensitivity in children with developmental dyslexia. *Reading and Writing*, **23**, 995–1019.

Goswami, U., Huss, M., Mead, N., Fosker, T., & Verney, J.P. (2013). Perception of patterns of musical beat distribution in phonological developmental dyslexia: significant longitudinal relations with word reading and reading comprehension. *Cortex*, **49** (5), 1363–1376.

Gross, J., Hoogenboom, N., Thut, G., Schyns, P., Panzeri, S., *et al*. (2013). Speech rhythms and multiplexed oscillatory sensory coding in the human brain. *PLoS Biology*, **11** (12), e1001752.

Guttorm, T.K., Leppänen, P.H.T., Hämäläinen, J.A., Eklund, K.M., & Lyytinen, H. (2010). Newborn event-related potentials predict poorer pre-reading skills in children at risk for dyslexia. *Journal of Learning Disabilities*, **43** (5), 391–401.

Hakvoort, B., van der Leij, A., Maurits, N., Maassen, B., & van Zuijen, T.L. (2015). Basic auditory processing is related to

familial risk, not to reading fluency: an ERP study. *Cortex*, **63**, 90–103.
Hämäläinen, J.A., Salminen, H.K., & Leppänen, P.H.T. (2012). Basic auditory processing deficits in dyslexia: systematic review of the behavioral and event-related potential/field evidence. *Journal of Learning Disabilities*, **46** (5), 413–427.
Hasson, U., Chazanfar, A., Galantucci, B., Garrod, S., & Keysers, C. (2012). Brain-to-brain coupling: a mechanism for creating and sharing a social world. *Trends in Cognitive Sciences*, **16**, 114–121.
Igarashi, Y., Nishikawa, K.Y., Tanaka, K., & Mazuka, R. (2013). Phonological theory informs the analysis of intonational exaggeration in Japanese infant-directed speech. *Journal of the Acoustic Society of America*, **134**, 1283–1294.
Kaplan, P.S., Bachorowski, J.A., Smoski, M.J., & Hudenko, W.J. (2002). Infants of depressed mothers, although competent learners, fail to learn in response to their own mothers' infant-directed speech. *Psychological Science*, **13** (3), 268–271.
Kitamura, C., & Burnham, D. (2003). Pitch and communicative intent in mother's speech: Adjustments for age and sex in the first year. *Infancy*, **4**, 85–110.
Kitamura, C., & Lam, C. (2009). Age-specific preferences for infant-directed affective intent. *Infancy*, **14**, 77–100.
Kubicek, C., De Boisferon, A.H., Dupierrix, E., Pascalis, O., Lœvenbruck, H., *et al*. (2014). Cross-modal matching of audio-visual German and French fluent speech in infancy. *PLoS ONE*, **9** (2), e89275.
Kuhl, P., Andruski, J.E., Chistovich, I.A., Chistovich, L.A., Kozhevnikova, E.V., *et al*. (1997). Cross-language analysis of phonetic units in language addressed to infants. *Science*, **277** (5326), 684–686.
Lam, C., & Kitamura, C. (2010). Maternal interactions with a hearing and hearing impaired twin: similarities and differences in speech input, interaction, and word production. *Journal of Speech, Language, and Hearing Research*, **53**, 543–555.
Lam, C., & Kitamura, C. (2012). Mommy, speak clearly: induced hearing loss shapes vowel hyperarticulation. *Developmental Science*, **15** (2), 212–221.
Leong, V., Kalashnikova, M., Burnham, D., & Goswami, U. (2014). Infant-directed speech enhances temporal rhythmic structure in the envelope. *15th Annual Conference of the International Speech Communication Association*, Singapore, 2563–2567.
Leppänen, P.H.T., Hämäläinen, J.A., Salminen, H.K., Eklund, K.M., Guttorm, T.K., *et al*. (2010). Newborn brain event-related potentials revealing atypical processing of sound frequency and the subsequent association with later literacy skills in children with familial dyslexia. *Cortex*, **46**, 1362–1376.
Leppänen, P.H.T., Richardson, U., Phko, E., Eklund, K.M., Guttorm, T.K., *et al*. (2002). Brain responses to changes in speech sound durations differ between infants with and without familial risk for dyslexia. *Developmental Neuropsychology*, **22** (1), 407–422.
Liu, H.M., Kuhl, P., & Tsao, F.M. (2003). An association between mothers' speech clarity and infants' speech discrimination skills. *Developmental Science*, **6** (3), F1–F10.
Lyytinen, H., Aro, M., Eklund, K., Erskine, J., Guttorm, T., *et al*. (2004). The development of children at familial risk for dyslexia: birth to early school age. *Annals of Dyslexia*, **54** (2), 184–220.
Lyytinen, P., Eklund, K., & Lyytinen, H. (2003). The play and language behavior of mothers with and without dyslexia and its association to their toddlers' language development. *Journal of Learning Disabilities*, **36** (1), 74–86.
Ma, W., Golinkoff, R.M., Houston, D.M., & Hirsh-Pasek, K. (2011). Word learning in infant-and adult-directed speech. *Language Learning and Development*, **7** (3), 185–201.
McMurray, B., Kovack-Lesh, K.A., Goodwin, D., & McEchron, W. (2013). Infant directed speech and the development of speech perception: enhancing development or an unintended consequence? *Cognition*, **129**, 362–378.
Martin, A., Schatz, T., Versteegh, M., Miyazawa, K., Mazuka, R., *et al*. (2015). Mothers speak less clearly to infants than to adults: a comprehensive test of the hyperarticulation hypothesis. *Psychological Science*, **26** (3), 341–347.
Mehler, J., Jusczyk, P., Lambertz, G., Halsted, N., Bertoncini, J., *et al*. (1988). A precursor of language acquisition in young infants. *Cognition*, **29**, 143–178.
Munhall, K.G., MacDonald, E.N., Byrne, S.K., & Johnsrude, I. (2009). Talkers alter vowel production in response to real-time formant perturbation even when instructed not to compensate. *Journal of the Acoustic Society of America*, **125**, 384–390.
Papoušek, M. (2007). Communication in early infancy: an area of intersubjective learning. *Infant Behavior and Development*, **30** (2), 258–266.
Parsons, C.E., Young, K.S., Murray, L., Stein, A., & Kringelbach, M.L. (2010). The functional neuroanatomy of the evolving parent–infant relationship. *Progress in Neurobiology*, **91** (3), 220–241.
Pennington, B. (2006). From single to multiple deficit models of developmental disorders. *Cognition*, **101**, 385–413.
Pennington, B.F., & Lefly, D.L. (2001). Early reading development in children at family risk for dyslexia. *Child Development*, **72**, 816–833.
Petelin, R., & Petelin, Y. (2003). *Cool Edit Pro 2 in Use*. Wayne, PA: A-List Publishing.
Plakas, A., van Zuijen, T., van Leeuwen, T., Thomson, J.M., & van der Leij, A. (2013). Impaired non-speech auditory processing at a pre-reading age is a risk-factor for dyslexia but not a predictor: an ERP study. *Cortex*, **49** (4), 1034–1045.
Richardson, U., Leppänen, P.H., Leiwo, M., & Lyytinen, H. (2003). Speech perception of infants with high familial risk for dyslexia differ at the age of 6 months. *Developmental Neuropsychology*, **23**, 385–397.
Scarborough, H.S., & Fichtelberg, A. (1993). Child-directed talk in families with incidence of dyslexia. *First language*, **13** (37), 51–67.
Schrank, F.A., & McGrew, K.S. (2001). *Woodcock-Johnson® III*. Itasca, IL: Riverside Publishing.
Smith, N.A., & Trainor, L.J. (2008). Infant-directed speech is modulated by infant feedback. *Infancy*, **13** (4), 410–420.
Snowling, M. (2000). *Dyslexia*. Oxford: Blackwell Publishing.

Soderstrom, M., Blossom, M., Foygel, R., & Morgan, J.L. (2008). Acoustical cues and grammatical units in speech to two preverbal infants. *Journal of Child Language*, **35** (04), 869–902.

Song, J.Y., Demuth, K., & Morgan, J. (2010). Effects of the acoustic properties of infant-directed speech on infant word recognition. *Journal of Acoustic Society of America*, **128** (1), 389–400.

Thiessen, E.D., Hill, E.A., & Saffran, J.R. (2005). Infant-directed speech facilitates word segmentation. *Infancy*, **7** (1), 53–71.

Torgesen, J.K., Wagner, R., & Rashotte, C. (1999). *TOWRE–2 Test of Word Reading Efficiency*. Austin, TX: Pro-Ed.

Uther, M., Knoll, M.A., & Burnham, D. (2007). Do you speak E-NG-L-I-SH? A comparison of foreigner- and infant-directed speech. *Speech Communication*, **49**, 2–7.

van der Leij, A., van Bergen, E., van Zuijen, T., de Jong, P.F., Maurits, N.M., *et al*. (2013). Precursors of developmental dyslexia: an overview of the longitudinal Dutch Dyslexia Programme study. *Dyslexia*, **19**, 191–213.

van Zuijen, T., Plakas, A., Maassen, B., Maurits, N.M., & van der Leij, A. (2013). Infant ERPs separate children at risk of dyslexia who become good readers from those who become poor readers. *Developmental Science*, **16** (4), 554–563.

Wechsler, D. (2014). *Wechsler Adult Intelligence Scale-Fourth Edition (WAIS–IV)*. San Antonio, TX: The Psychological Corporation.

Xu, N., Burnham, D., Kitamura, C., & Vollmer-Conna, U. (2013). Vowel hyperarticulation in parrot-, dog- and infant-directed speech. *Anthrozoos*, **26** (3), 373–380.

Received: 22 April 2016
Accepted: 12 July 2016