Sensitivity to amplitude envelope rise time in infancy and vocabulary development at three years: A significant relationship

Short running title: **Rise time and vocabulary development**

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Data availability: All data reported here are available upon request to the first author.

Research Highlights

- The ability to discriminate amplitude envelope rise times has been linked to successful phonological development, but its role in predicting early linguistic attainment remains undefined.
- Rise time discrimination at 7 and 10 months, and phonological sensitivity and vocabulary at 3 years were assessed in children at-risk for dyslexia and controls.
- Rise time sensitivity in infancy was a significant predictor of vocabulary at 3 years of age.
- The significant relationship between amplitude envelope rise time discrimination and vocabulary suggests that infants with better rise time sensitivity process the speech signal more effectively.

Abstract

Here we report, for the first time, a relationship between sensitivity to amplitude envelope rise time in infants and their later vocabulary development. Recent research in auditory neuroscience has revealed that amplitude envelope rise time plays a mechanistic role in speech encoding. Accordingly, individual differences in infant discrimination of amplitude envelope rise times could be expected to relate to individual differences in language acquisition. A group of 50 infants taking part in a longitudinal study contributed rise time discrimination thresholds when aged 7 and 10 months, and their vocabulary development was measured at 3 years. Experimental measures of phonological sensitivity were also administered at 3 years. Linear mixed effects models taking rise time sensitivity as the dependent variable, and controlling for non-verbal IQ, showed significant predictive effects for vocabulary at 3 years, but not for the phonological sensitivity measures. The significant longitudinal relationship between amplitude envelope rise time discrimination and vocabulary development suggests that early rise time discrimination abilities have an impact on speech processing by infants.

Keywords: amplitude envelope rise time, dyslexia, auditory perception, vocabulary, family risk, speech processing

Children's perception of the amplitude modulation structure of speech is increasingly recognised to play a role in individual differences in language development (Goswami, 2018). The speech amplitude envelope, the relatively slow modulations in intensity in speech over time, offers a complementary way of conceptualising temporal changes in the speech signal to the speech spectrogram, which depicts the presence of energy across frequency over time (see Leong & Goswami, 2015). While the speech spectrogram foregrounds the potential importance of cues such as rapid frequency changes for individual differences in language development, a focus on the amplitude modulation structure of speech foregrounds the potential importance of amplitude envelope rise time discrimination. Amplitude envelope rise times or "auditory edges" are the rates at which amplitude modulations in the speech signal increase. During neural speech encoding, amplitude rise times are used by cortical networks to synchronise or phase-reset their oscillatory activity with matching temporal information in speech (Giraud & Poeppel, 2012 for a review). Accordingly, amplitude envelope rise times play a role in successful speech encoding and comprehension (Doelling, Arnal, Ghitza, & Poeppel, 2014). In behavioural studies, individual differences in school-aged children's sensitivity to amplitude envelope rise times are a significant predictor of their phonological processing and reading abilities (see Goswami, 2015 for a review). However, it remains unknown whether early indices of rise time discrimination in infancy also have an impact on the development of earlier and more general linguistic abilities such as vocabulary development. Here we investigate this question in infants who are and are not at family risk for later language delay, specifically developmental dyslexia.

Extensive behavioural evidence demonstrates that accurate discrimination of amplitude rise times is important for linguistic development in children. For example, a series of studies with children with developmental dyslexia, a learning disorder that affects reading and spelling and which is characterised by a linguistic phonological deficit, has shown impaired discrimination of amplitude rise times in children across ages (7 to 11 years) and across languages (English, French, Hungarian, Chinese, Spanish, Dutch, and Finnish; see Goswami et al., 2002; 2011a; Muneaux, Ziegler, Truc, Thomson, & Goswami, 2004; Hämäläinen et al., 2009; Surányi et al., 2009; Poelmans et al., 2011). Further, individual differences in language-relevant phonological awareness tasks have been found to be associated with individual differences in rise time discrimination in these studies. For example, rise time discrimination is associated with tone awareness in Chinese, with phoneme awareness in Spanish, and with rhyme awareness in English (Goswami et al., 2011a). Studies of preschool children at family risk for dyslexia also find that rise time discrimination is related to a range of phonological precursors for reading (Vanvooren, Poelmans, De Vos, Ghesquiere, & Wouters, 2017). As might be expected given the core role of amplitude rise times in speech encoding (Doelling et al., 2014), children with dyslexia also show atypical neural phase entrainment to the speech signal. Accordingly, studies of children with dyslexia speaking both English (Power, Mead, Barnes, & Goswami, 2013; Power, Colling, Mead, Barnes, & Goswami, 2016) and Spanish (Molinaro, Lizarazu, Lallier, Bourguignon, & Carreiras, 2016) have shown atypical neural entrainment in the delta band in syllable, sentence, and story listening tasks.

Despite their difficulties with phonological awareness, children with dyslexia typically appear to have normal speaking and listening skills and good vocabulary. Given their documented rise time difficulties, this may appear surprising. However, this may be due to the inclusion of older children, typically aged eight years or older, in most studies of dyslexia. The effects of dyslexia on the development of receptive and expressive vocabulary size are most evident at earlier stages of language acquisition. Prospective studies of younger children at family (genetic) risk of dyslexia do show deficits in expressive vocabulary (in 17-month-olds acquiring Dutch, Koster et al., 2005) and receptive vocabulary in preschool children aged 40 months (Scarborough, 1990). More recently, van Viersen et al. (2017) showed that children at-risk for dyslexia exhibit delayed growth patterns of both receptive and expressive vocabulary sizes from 17 to 35 months, and that these early vocabulary scores reliably discriminated between at-risk children who do and do not develop dyslexia. Some prospective studies of dyslexia also demonstrate subtle differences in speech production. For example, Smith, Lambrecht Smith, Locke, and Bennett (2008) documented impairments in syllable timing in the spontaneous speech of at-risk toddlers compared to those not at-risk at both two and three years of age.

In the first family risk study of dyslexia to measure sensitivity to amplitude rise time in infancy, we have been following a cohort of infants who are either at family risk (FR) of developing dyslexia given dyslexia in one or both parents, and in a control group of infants (CTR) who are not at family risk but at general population risk of developing dyslexia. We previously reported significantly poorer sensitivity to amplitude rise time in the FR group than the CTR group at 10 months (Kalashnikova, Goswami, & Burnham, 2018). Here we report on a larger group of the FR and CTR infants. These infants contributed rise time thresholds at both seven and 10 months, and then also contributed language outcome measures at three years of age. We expected to replicate our earlier finding of impaired rise time discrimination in the FR compared to the CTR group, and we also expected that, irrespective of group assignment, infants with higher rise time discrimination thresholds (poorer sensitivity) would develop smaller vocabularies and exhibit reduced phonological sensitivity.

Method

Participants

Fifty children were included in this study: 22 (9 female) were at family risk for dyslexia (FR) and 28 (16 female) were not at family risk for any developmental disorders (CTR). All children were recruited to participate in the longitudinal Seeds of Literacy project investigating early precursors of dyslexia when they were five months of age, and they continued to participate in regular laboratory visits until the age of five years.

The sample described above was selected based on data availability for the infant portion of this study (rise time discrimination tasks completed at seven and 10 months of age). An additional 25 infants also completed these tasks, but their data were excluded from all subsequent analyses due to being at risk for other developmental disorders (1), hearing deficits (2), and failure to comply with the inclusion criteria for the amplitude rise time discrimination task (22; see Procedure below).

All children were typically-developing and growing up in English language-dominant families. Children's assignment to the FR and CTR groups was based on their parents' performance on a comprehensive battery of language, reading, and cognitive tasks. In order to be assigned to the FR group, one of the child's parents was required (1) to score 1.5SD below the mean in a measure of word and non-word reading and a measure of phonological awareness, (2) indicate history of experiencing reading difficulties in childhood, and (3) have average non-verbal IQ. In order to be assigned to the CTR group, both parents were required to obtain scores within .5SD of the mean on all the screening tests. Maternal education level was used as a proxy of participants'

Socio-Economic Status. The Median level was a university degree, and the median did not differ between the CTR and FR groups (Kolmogorov-Smirnov $Z = .148$, $p = 1.0$).

The amplitude rise time discrimination task was administered at the ages of seven months (CTR $M = 31.29$ weeks, $SD = 1.09$; FR $M = 30.9$ weeks, $SD = 1.49$) and 10 months (CTR $M = 44.03$ weeks, $SD = .77$; FR weeks $M = 43.48$, $SD = 1.23$) and the phonological sensitivity tasks, the standardised vocabulary test, and the non-verbal IQ test at the age of 36 months (CTR $M = 36.23$ months, $SD = .36$; FR $M = 36.38$ months, $SD = .39$). In addition, the phonological sensitivity tasks were also administered a second time at 42 months (CTR $M = 42.41$ months, $SD = .57$; FR $M = 42.45$ months, $SD = .44$).

Data for the 36 and 42 month child tasks were not available for 8 of the original 50 children included in the infant portion of this study: 7 children (5 CTR, 2 FR) failed to return to the lab for the later assessments and 1 (FR) only contributed vocabulary and IQ data but failed to comply with the instructions for the phonological sensitivity tasks. Therefore, the sample size for analyses that included the infant task only was 50 (28 CTR, 22 FR), and the sample size for analyses that included the infant and the child tasks was 42 (23 CTR, 19 FR).

Amplitude Rise Time Discrimination Task

Stimuli. Twenty pure sinewave tones (500 Hz) 800ms in duration were used to construct the auditory stimuli. The duration to maximum rise time of the tones was manipulated systematically, increasing from 15ms (steady state portion 735ms, fall time 50ms) to 300ms (steady state portion 450ms, fall time 50ms) in 15ms intervals. During the presentation of the audio stimuli, infants were presented with images of colourful checkerboards to capture and maintain their attention to the task.

Stimulus presentation was controlled using a MATLAB (Mathworks, Natick, USA) script presented on a computer running Windows XP. Three 22-inch computer monitors placed side by side were used to present the visual stimuli. Checkerboards appeared on the left and right monitors, and the central monitor was used to display an attention getting visual stimulus to re-engage the infants' attention to the centre of the set up between trials. Auditory stimuli were presented over loudspeakers hidden behind the right and left monitors.

Procedure. The amplitude rise time discrimination task (Kalashnikova et al., 2018) is an infant adaptation of a two alternative forced-choice (2AFC) adaptive threshold procedure (Goswami, Fosker, Huss, Mead & Szücs, 2011b). Infants sat on their parents' lap facing the three computer monitors located side by side in a quiet room inside an infant laboratory. Parents listened to masking sounds over noise-cancelling headphones and were instructed not to interfere with the task and to avoid speaking to their infant or pointing to the screen. At the start of the task and between experimental trials, infants were presented with an attention getter (a circular shape expanding and contracting in silence) on the central screen. After infants had fixated the centre monitor for 2 seconds, the attention getter disappeared, and the images of checkerboards appeared on the left and right screens. When infants fixated one of the sides (counterbalanced across participants), their fixations triggered the presentation of a repeating stimulus with the same rise time (15ms, 15ms, 15ms, 15ms, etc.), and when they fixated the other side, their fixations triggered the presentation of alternating stimuli with different rise times (15ms, 300ms, 15ms, 300ms, etc.). Greater (≥55%) fixation to the alternating stimulus side for two consecutive trials resulted in a step down (e.g., 15ms, 270ms, 15ms, 270ms, ...), and less than 55% to a step back up (i.e., a reversal occurred every time that the steps changed direction) on the alternating side sound but no change to the repeating side sound. Testing continued for 25 trials.

The initial side assignment of the alternating and the repeating stimuli was maintained during the first 22 trials. During the last 3 trials of the task (trials 23-25), the repeating and alternating sides were reversed to control for any side preference the infant may have. Infants' data were not included in the final analyses if they failed to fixate for a minimum of 10% of looking time to the new side of the alternating stimulus averaged across these 3 control trials.

Infants' looking times to the alternating and repeating sides during the 22 experimental trials (1-22) prior to the side reversal were recorded and used for analyses. These looking time data provide an index of infants' overall engagement in the task and their overall discrimination of rise times given by the relative attention to the alternating vs. the repeating stimuli. A more specific measure is each individual's threshold for rise time discrimination, which was possible to calculate due to the adaptive nature of the paradigm. Individual's thresholds were calculated as the rise time difference between the two rise times in the alternating stimuli presented for the last three step reversals. Infants who failed to complete at least three reversal steps were not included in the analyses. On average, infants completed 4 reversals in the task at both 7 months (CTR *M* = 4.74, *SD* = 1.52; FR *M* = 4.33, *SD* = 1.43) and 10 months of age (CTR *M* = 4.26, *SD* = 1.15, FR *M* = 3.94, *SD* = 1.29). Fifty-seven sessions i.e., session refers to a 7-month or a 10-month recording for an infant) were excluded based on this criterion (at 7 months: 19 FR and 15 CTR; at 10 months: 11 FR and 12 CTR) resulting in the exclusion of 22 infants from this study (see Participants).

Tasks of Phonological Sensitivity, Vocabulary and Non-verbal IQ

Mispronunciation detection task. In this task, children were presented with an image of an object on a computer screen and heard an audio recording of that object's label, which was either correctly or incorrectly pronounced. Mispronunciations were constructed by substituting one of the phonemes in the object's label (see Appendix Table A1 for item list). Children were instructed to "say whether the lady says the word right". The task included 3 practice words and 20 test words, which were administered in their correct and mispronounced forms yielding a total of 6 practice and 40 test trials. For each trial, the experimenter recorded whether the child said 'yes' (signifying correct pronunciation), 'no' (signifying incorrect pronunciation), or whether the child failed to respond. Subsequently, the number of hits (correct detection of mispronunciations) and false positives (rejection of correct pronunciation) were calculated and used to compute a mispronunciation detection index: (hits - false positives)/total number of trials.

Non-word repetition task. In this task, children were introduced to a hand puppet, and told that the puppet was an alien from a different planet who spoke an alien language. Children were then asked to learn some of the words of the alien language by repeating them after the puppet. While the experimenter manipulated the puppet, the stimuli were played over loud speakers. The task included four practice items, and 16 test items. The test items were split into three categories: 1-syllable (6 items), 2-syllables (6 items), and 3-syllables (4 items) (see Appendix Table A2 for stimulus list). Each item was presented twice before the child was asked to respond. The experimenter coded whether the child's production of the word matched or mismatched its target form. Only identical repetitions were coded as correct. The numbers of first attempt correct, second attempt correct, total correct attempted, total incorrect, and missing responses were computed. The proportion of correct responses out of the total recorded responses was used for analyses.

Vocabulary. The Knowledge Vocabulary sub-test in the Routing-Verbal Domain of the Stanford-Binet Intelligence Scales-5th Edition (Roid, 2003) was administered. This test assesses children's receptive and expressive vocabulary skills. A single scaled score (*M* = 10; *SD* = 3) computed based on the combination of receptive and expressive vocabulary test items was calculated for each child and used for analyses.

Non-verbal IQ. The Fluid Reasoning Object Series/Matrices sub-test in the Routing-Non-verbal Domain of the Stanford-Binet Intelligence Scales-5th Edition (Roid, 2003) was administered as the measure of non-verbal IQ. Scaled scores (*M* = 10; *SD* = 3) were computed and used for analyses.

Results

Comparison of FR and CTR Infants' Amplitude Rise Time Discrimination

Infants' performance was analysed using Linear Mixed Effects (LME) models conducted using the lme4 package in R (Bates, 2005), and the lmerTest package (Kuznetsova, Brockhoff, & Christensen, 2015) was used to compute *p*-values and conduct pairwise comparisons to investigate significant interactions. Raw looking times computed in milliseconds were transformed into log scores following the recommendations of Csibra and colleagues for the statistical treatment of infant looking time data (Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016). Log transformations were also applied to raw rise time discrimination thresholds. All data reported in this article are available upon request to the first author.

First, a model was fitted to infants' log transformed fixation durations (indexing infant interest) in response to the alternating and repeating stimuli in order to confirm the efficacy of this task in maintaining infants' engagement across trials and adapting the trial difficulty to their individual performance. If infants were engaged in the task and were responding to the stimuli, they were expected to direct significantly longer looking times to the side playing the alternating than the repeating stimuli. The LME model was constructed with fixation durations as the dependent variable, and group (FR, CTR), age (7 months, 10 months), and trial type (Alternating, Repeating) as the independent variables, and random intercepts for participant and trial number (see Appendix Table A3 for model output).

The model yielded no main effects of risk status group, $F(1, 47.30) = 3.437$, $p = .07$, or age, $F(1, 430.85) = 2.977$, $p = .09$, but a main effect of trial type, $F(1, 1710.14) = 60.79$, $p < .001$. The group by age, $F(1, 450.39) = .063$, $p = .81$, group by trial type, $F(1, 1713.53) = 2.239$, $p = .13$, and age by trial type, $F(1, 1714.39) = 1.436$, $p = .23$, interactions were not significant, but the three-way interaction of risk status group by age group by trial type was significant, $F(1, 1709.16) = 5.886$, $p = .015$. Pairwise comparisons showed that infants directed significantly longer fixations to alternating than to repeating trials in the CTR group, $\beta = 0.287$, $SE = 0.042$, $CI[0.204, 0.371]$, $t(1355.0) = 6.765$, $p < .001$, and in the FR group, $\beta = 0.211$, $SE = 0.051$, $CI[0.113, 0.309]$, $t(1091.3) = 4.203$, $p < .001$ (see Figure 1). This suggests that infants engaged in the task and showed the tendency to attend to the side of presentation of the more interesting alternating stimuli.

A second LME model was fitted to infants' rise time discrimination thresholds to assess discrimination performance across age and groups. The model included group (CTR, FR) and age (7 months, 10 months) as the independent variables, and random intercepts for participant and reversal number (see Appendix Table A4 for model output). Infants' rise time discrimination thresholds are shown in Figure 2.

The model yielded no main effect of risk status group, $F(1, 47.87) = .295$, $p = .59$, a marginal effect of age group, $F(1, 68.28) = 3.939$, $p = .051$, and a significant risk status group by age group interaction, $F(1, 68.144) = 8.398$, $p = .005$. Follow-up pair-wise comparisons showed that while CTR and FR infants' performance did not differ significantly at 7 months, $\beta = -.270$, $SE = .176$, $CI[.082, .129]$, $t(58.2) = 1.538$, $p = .129$, or at 10 months, $\beta = .050$, $SE = .171$, $CI[-.293, .394]$, $t(53.1)=.294$, $p = .769$, the group by age interaction was due to a significant difference in performance between 7 and 10 months of age in the CTR group, $\beta = 0.242$, $SE = 0.071$, CI[0.102, 0.383], $t(163.5) = 3.405$, $p = .001$, but not in the FR group, $B = -0.078$, $SE = 0.084$, $CI[-0.244, 0.088]$, $t(164.8)= -0.932$, $p = .352$. Perceptual sensitivity improved as a function of age from 7 to 10 months in the CTR group but remained unchanged over age in the FR group.

Relation between Rise Time Discrimination Thresholds, Phonological Sensitivity, and Vocabulary Skills in Early Childhood

Children's scores for phonological sensitivity measures at 36 and 42 months, and vocabulary and non-verbal IQ at 36 months, along with results of independent-sample *t*-tests comparing FR and CTR scores are shown in Table 1. As predicted, scores for the FR group were consistently lower for these verbal tasks; however, the group differences were not significant. Non-verbal IQ was significantly lower for the FR than the CTR group, but the FR group's scores were within age norms, a pattern consistent with previous research with children at-risk for dyslexia (van Bergen et al., 2014).

The analyses of FR and CTR infants' performance on the rise time discrimination task indicate significant early differences in the developmental trajectory for perceptual sensitivity in the two groups. In addition, we were interested in assessing whether rise time discrimination could be classified retrospectively based on 36- and 42-month-old children's phonological sensitivity and vocabulary skills.

For this purpose, we required a single measure of phonological sensitivity. In order to obtain single scores for each phonological sensitivity task suitable for use as a predictor variable, a factor analysis was conducted on the four phonological sensitivity scores (mispronunciation detection at 36 months, non-word repetition at 36 months, mispronunciation detection at 42 months, and non-word repetition at 42 months). This also allowed us to maximise the availability of individual scores for these measures (see Participants for information about missing data for these tasks). As expected, the factor analysis yielded two factors: Factor 1 – mispronunciation detection, and Factor 2 – non-word repetition (see Appendix Table A5 for details of the Factor analysis). Each individual score on each task was multiplied by the corresponding factor loading resulting in weighted factor scores for each participant. Finally, the weighted scores for 36 and 42 months were averaged producing a weighted score for mispronunciation detection and for non-word repetition (see Table 1). Inspection of simple correlations between the tasks revealed that the two experimental measures of phonological sensitivity showed higher correlations with the composite vocabulary measure (mispronunciation detection, $r(43) = .481$, $p = .001$; non-word repetition, $r(42) = .505$, $p = .001$, than with each other, $r(42) = .327$, $p = .034$).

To assess the relation between rise time discrimination thresholds, phonological sensitivity, and vocabulary, an LME model was constructed with rise time discrimination thresholds as the dependent variable, and age of rise time task administration (7 months, 10 months), mispronunciation detection score, non-word repetition score, composite vocabulary score, and non-verbal IQ score as independent variables, and random intercepts for participants and reversal number (see Appendix

Table A6 for model output). The resulting model (see Figure 3) showed that the only significant predictor of children's rise time performance in infancy was their composite vocabulary at three years of age, $F(1, 37.101) = 5.695$, $p = .022$, $\beta = -.111$, $SE = .047$, $t(36.152) = -2.386$, $p = .022$, with no significant effects of age of infant task administration, $F<1$, mispronunciation detection score, $F<1$, non-word repetition score, $F(1, 37.018) = 1.431$, $p = .239$, or non-verbal IQ, $F<1$. Accordingly, language outcomes at three years do indeed show a relationship to early sensitivity to amplitude envelope rise time.

Discussion

This is the first study to investigate whether individual differences in perceptual sensitivity to amplitude envelope rise time measured in infancy are related to language development in the preschool years. There was no difference in rise time sensitivity between FR and CTR infants at seven months, but sensitivity improved between seven and 10 months for the CTR but not the FR infants. These data are concordant with the significantly poorer rise time sensitivity at 10 months reported for a sub-set of these FR infants by Kalashnikova and colleagues (Kalashnikova et al., 2018). The lack of a significant group difference here at 10 months may relate to differences in the size of the FR and CTR samples, and/or to their composition given that the dyslexia status of the FR infants has still not been determined. While the FR samples in the two studies include infants at family risk for dyslexia, we are unable to determine whether these samples have equal distributions of risk children who will and will not later manifest dyslexia in childhood, and this distinction can have an impact on group-level auditory processing patterns in infants (Guttorm et al., 2005; 2010; van Zuijen, Plakas, Maassen, Maurits, & van der Leij, 2013).

As three-year-olds, the FR children showed consistently lower scores in the vocabulary and phonological sensitivity measures, but again the observed differences were not significant. Nevertheless, the wide range of scores enabled longitudinal relationships to be assessed. It was found that the only significant retrospective predictor of infant rise time sensitivity was vocabulary size at three years. Infants who were more sensitive to rise time had larger vocabularies as three-year-olds. Contrary to expectation, the phonological sensitivity measures, non-word repetition and mispronunciation, were not significantly related to rise time thresholds, despite the FR children showing poorer phonological sensitivity. While rise time sensitivity measured prior to schooling has been demonstrated to be a reliable predictor of phonological processing in at-risk children (Plakas et al., 2013; Vanvooren et al., 2017), in these studies phonological processing was measured when children were in Grades 1 and 2, much older than the age of 36 months measured here. Hence as we continue to follow our FR and CTR children longitudinally, rise time may also become a significant predictor of individual differences in phonological processing at a later age. Further, we used experimental measures to assess phonological sensitivity, rather than standardised measures as for vocabulary. Standardised measures of phonological development may have been more suited to revealing predictive relationships. Indeed, correlations between the language outcome tasks showed that both phonological sensitivity measures were more strongly related to the vocabulary measure than to each other. This suggests that our experimental tasks were not discriminative regarding early phonological sensitivity independent of general vocabulary development.

The significant relationship between early rise time sensitivity and later vocabulary found here suggests that individual differences in early perceptual sensitivity have developmental effects on early language acquisition (see also Choudhury &

Benasich, 2011). As both children with oral developmental language disorder (DLD) and with developmental dyslexia show impaired discrimination of amplitude rise times (Beattie & Manis, 2012), the demonstration here of developmental effects on receptive and expressive vocabulary development may offer new avenues for exploring the basis of the linguistic deficits exhibited in these developmental disorders. Sensitivity to amplitude envelope rise time in infancy may well be an important developmental marker of later oral and written language impairment.

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Table 1.

CTR and FR children's scores for the phonological awareness, vocabulary, and non-verbal IQ tasks.

Task	CTR	FR	*t*-test	*p*-value	*n*
Mispronunciation detection 3 years[1]	.53 (.13)	.49 (.18)	0.938	.354	42
Non-word repetition 3 years[2]	.48 (.19)	.45(.22)	0.509	.613	42
Mispronunciation detection 3.5 years[1]	.62 (.24)	.591 (.21)	0.444	.659	42
Non-word repetition 3.5 years[2]	.58 (.23)	.44 (.22)	1.969	.057	42
Non-verbal IQ 3 years[3]	11.78 (2.45)	10.25 (1.86)	2.283	.028	43
Vocabulary 3 years[4]	11 (2.68)	10.5 (2.14)	.669	.507	43
Mispronunciation detection (Weighted Mean score)[5]	.50 (.128)	.467 (.156)	.756	.454	42
Non-word repetition (Weighted Mean score)[5]	.44 (.151)	.385 (.166)	1.20	.237	42

[1] Mispronunciation detection index; [2] proportion of correct responses; [3] scaled score on The Knowledge Vocabulary sub-test in the Routing-Verbal Domain of the Stanford-Binet Intelligence Scales-5th Edition (*M* = 10, *SD* = 3); [4] scaled score on The Fluid Reasoning Object Series/Matrices sub-test in the Routing-Non-verbal Domain of the Stanford-Binet Intelligence Scales-5th Edition; [5] Weighted mean scores computed averaging the weighted scores for 3 and 3.5 years for each phonological sensitivity task.

List of Figures

Appendix

Table A1.

Mispronunciation detection task stimuli

		Practice	
Apple	**Abble*	Puppy	**Pukky*
Money	**Noney*		
		Test	
Toothpaste	**Koothpaste*	Mushroom	**Nushroom*
Rooster	**Looster*	Lizard	**Livard*
Camel	**Gamel*	Eyelash	**Eyewash*
Bucket	**Pucket*	Balloon	**Banoon*
Peacock	**Peagock*	Mailbox	**Bailbox*
Rainbow	**Wainbow*	Island	**Isnand*
Fireman	**Fireban*	Table	**Taple*
Turtle	**Kurtle*	Rabbit	**Rappit*
Carrot	**Callot*	Hammer	**Hanner*
Guitar	**Guikar*	Window	**Rindow*

Table A2.

Non-word repetition task stimuli

		Practice	
Pemmie	Nape	Diff	Metton
		Test	
Nuck	Gick	Dinnick	Fean
Pame	Gattom	Katapet	Pennell
Hom	Baddep	Suppennack	Derappin
Sep	Hammett	Megatess	Sallan

Table A3.

Output of LME model on FR and CTR infants' fixation durations in the rise time discrimination task

	Estimate	SE	df	*t*	*p*
Intercept	.729	.066	197.828	110.863	<.001
Group (CTR)	.042	.085	182.122	.491	.624
Age Group (10 mos)	-.128	.0746	1153.134	-1.710	.087
Trial Type (Non-Alt)	-.264	.077	2448.229	-3.409	.001
Group (CTR) × AgeGroup (10 mos)	.174	.101	906.141	1.737	.083
Group (CTR) × Trial Type (Non-Alt)	.084	.099	2446.778	.852	.394
Age Group (10 mos) × Trial Type (Non-Alt)	.102	.099	2449.139	1.035	.301
Group (CTR) × AgeGroup (10 mos) × Trial Type (Non-Alt)	-.318	.131	2449.833	-2.427	.015

Table A4.

Output of LME model on FR and CTR infants' rise time discrimination thresholds in the rise time discrimination task

	Estimate	SE	df	*t*	*p*
Intercept	.469	.133	61.124	35.209	<.001
Group (CTR)	.271	.176	58.238	1.538	.129
Age (10 mos)	.078	.084	164.827	.932	.353
Group (CTR) × Age (10 mos)	-.321	.111	164.285	-2.912	.004

Table A5.

Factor analysis including mispronunciation detection and non-word repetition scores at 36 and 42 months

Component	Variables	Component factor score	Eigenvalue	% Accumulated variance
1.Mispronunciation detection	36 months score 42 months score	.852 .875	1.573	39.32
2.Non-word repetition	36 months score 42 months score	.807 .896	1.494	76.66

Table A6.

Output of LME model assessing the relation between FR and CTR infants' rise time discrimination thresholds and their later phonological sensitivity and vocabulary skills

	Estimate	SE	df	*t*	*p*
Intercept	.571	.621	36.344	9.184	<.001
Age (10 mos)	-.029	.047	134.806	-.643	.521
Mispronun. Det.	-.426	.756	36.087	-.563	.577
Non-word rep.	.795	.665	36.071	1.196	.239
Vocabulary	-.111	.047	36.152	-2.386	.022
IQ	.015	.043	35.789	.344	.733

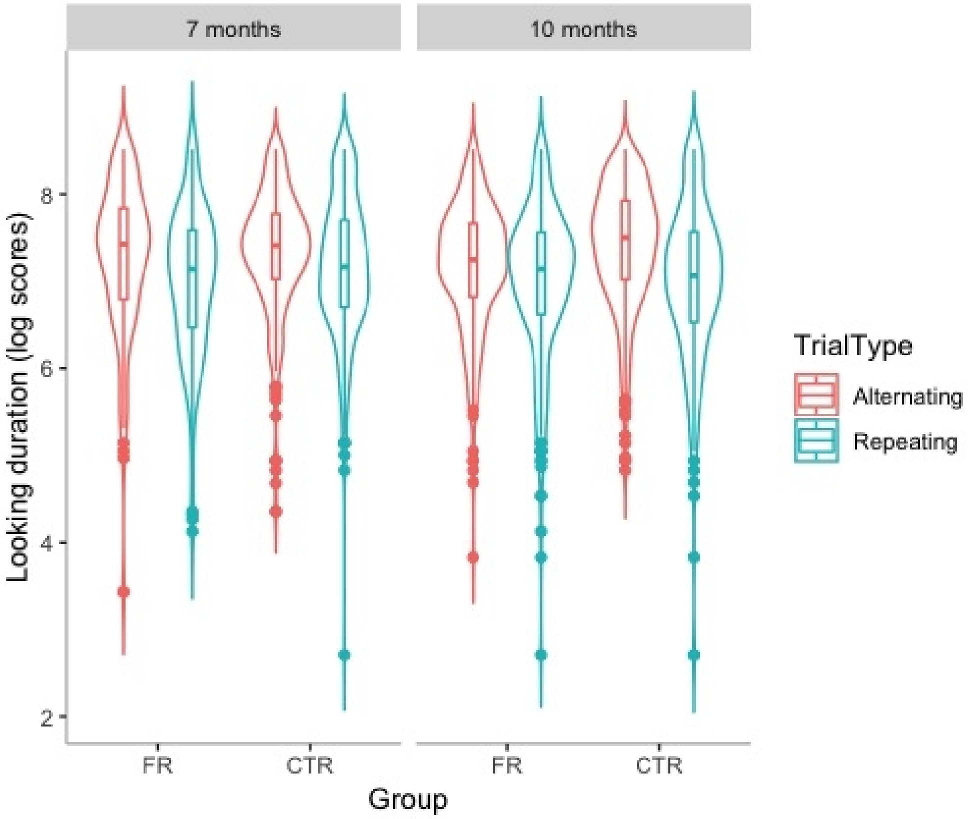

Figure 1. FR and CTR infants' fixation duration (after log transformation) in response to the alternating and repeating stimuli of the amplitude rise time discrimination task at 7 and 10 months.

179x150mm (72 x 72 DPI)

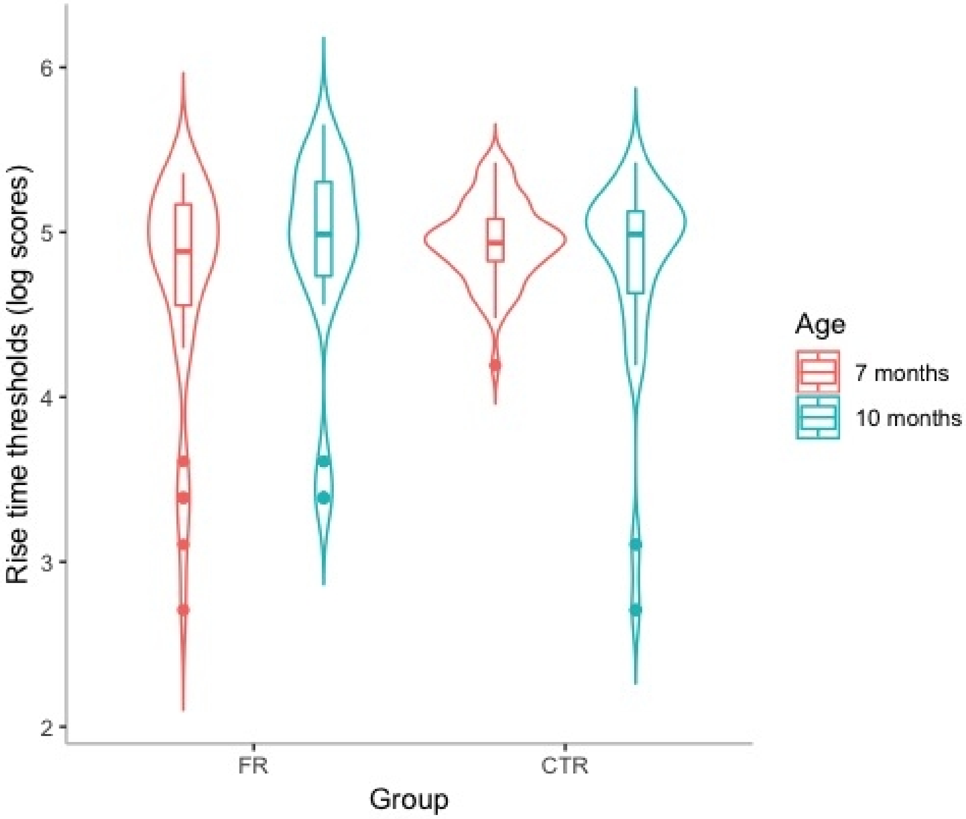

Figure 2. FR and CTR infants' discrimination thresholds (after log transformation) at 7 and 10 months in the amplitude rise time discrimination task.

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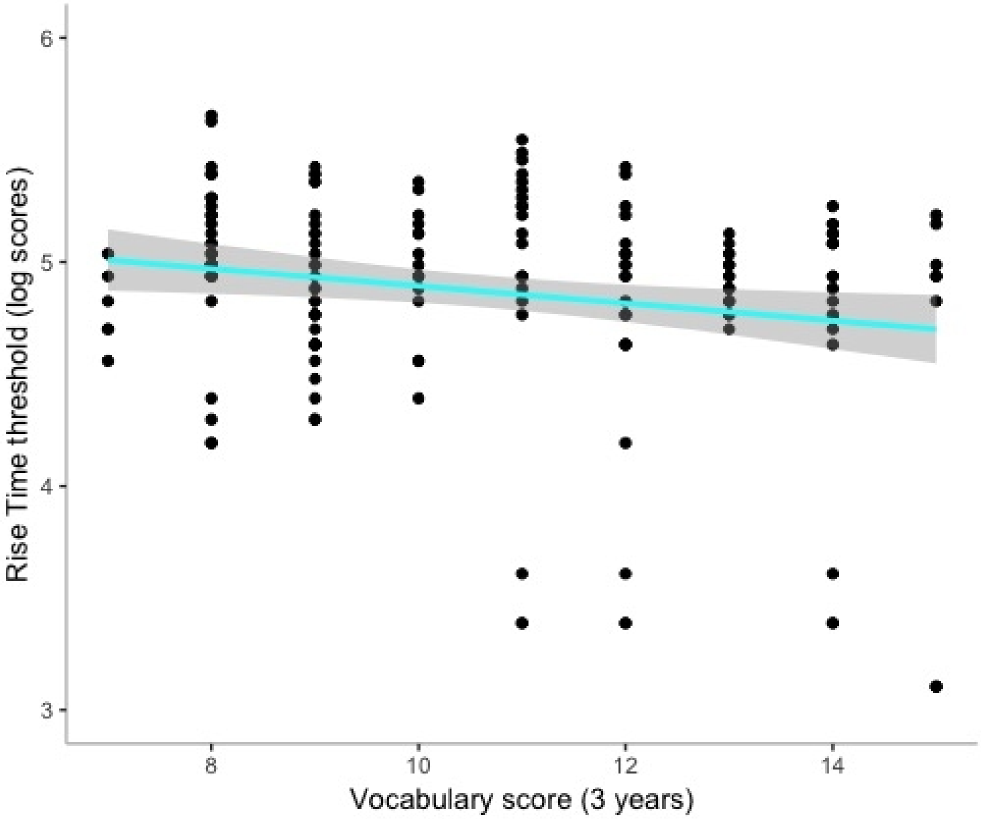

Figure 3. Amplitude rise time thresholds (after log transformation) displayed as a function of vocabulary scores at 3 years of age with LME model fit.

179x150mm (72 x 72 DPI)