Brain Potentials for Word Segmentation at Seven Months Predict Later Language Development

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1. Introduction

A lexicon maps words to concepts. For infants starting to acquire a lexicon, successfully mapping between word and concept requires not only being able to identify the concept, but crucially, also being able to identify the word (Waxman & Lidz, 2006). This is not as easy as it seems, since infants mainly hear multi-word utterances (Morgan, 1996; Van de Weijer, 1998; Woodward & Aslin, 1990), with pauses in the speech signal not corresponding reliably to word onsets. Hence, the ability to segment words from speech is vital for vocabulary acquisition.

Most of the cues that listeners can exploit to segment speech are learned through native language experience (Cutler, 2002). These cues are probabilistic rather than fully reliable; no single cue is sufficient to detect word boundaries. As Jusczyk, Houston & Newsome (1999) showed, an important cue for infants learning stress-based languages is that a stressed syllable signals word onset for a majority of words (Cutler & Carter, 1987, for English; Schreuder & Baayen, 1994; for Dutch). Infants who are 7.5 months old can recognize infrequent strong-weak words such as *hamlet*, but only by 10.5 months can they recognize infrequent words with the opposite, weak-strong pattern, such as *guitar*. Other language-specific cues that infants can use are the phonetic and phonotactic regularities in the native language (e.g., Mattys, Jusczyk, Luce & Morgan, 1999).

Newman, Bernstein Ratner, Jusczyk, Jusczyk & Dow (2006) have recently demonstrated that performance on speech segmentation tasks, but not on tasks measuring language discrimination or prosodic preferences, is related to expressive vocabulary at 24 months. Infants who, between 7.5 and 12 months, conformed to the overall group performance in language-segmentation studies had a larger expressive vocabulary later, compared to infants who did not produce this pattern. This difference in language achievement was still visible when these children were between four and six years old: performance on standardized language tests was significantly higher for 'segmenters', though the

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groups did not differ in overall intelligence quotients. Other evidence comes from a study (Graf-Estes, Evans, Alibali & Saffran, 2007) in which 17-month-old infants were first familiarized with an artificial language stream, and then taught a novel word. This novel word was either a whole word or part-word from the language stream. Infants showed only signs of subsequent word recognition when this novel word was a whole word but not when it was a part-word, demonstrating that the ability to segment words from speech is central to making a successful word-concept mapping.

Jusczyk and Aslin (1995) were the first to use the headturn-preference procedure to study word segmentation in infants, by modifying the original paradigm (Fernald, 1985) into a familiarization period followed by a test phase. After hearing highly frequent words several times in isolation (familiarization period), 7.5-month-olds attend in the test phase longer to passages containing these words, compared to passages containing unfamiliarized words.

However, it is also possible to study infants' ability to recognize words in running speech by recording event-related brain potentials (ERPs). This electrophysiological measure has the advantage of providing an online measure of word segmentation. Also, it is a more direct measure, since infants are not required to make any overt behavioral response. As Aslin & Fiser (2005) noted, it is difficult to interpret null results in behavioral infant studies, because there is always the possibility that infants fail to show a preference for one situation above the other, yet are able to distinguish between the two situations. Kooijman, Hagoort & Cutler (2005) were the first to develop an ERP analogue of Jusczyk et al.(1999)'s study. They tested Dutch infants first at ten months, an age at which they behaviorally have been shown to segment trochaic words from speech (Kuijpers, Coolen, Houston & Cutler, 1998). Infants heard a maximum of 20 familiarization and test phase blocks. Per block, infants first heard a low-frequent trochaic word such as *hommel* ('bumblebee') ten times in isolation, followed by eight sentences in random order, half containing the familiarized word in mid-sentence position, half containing a similar low-frequency word, such as *viking* ('Viking'). See Table 1 for an example of a block. The ten isolated words resemble the familiarization phase, and the eight sentences resemble the test phase of Jusczyk et al.(1999)'s first experiment. Event-related potentials were subsequently calculated by averaging over the familiarized words in sentences and over the unfamiliar words (with a minimum of ten trials per subject average per condition). There was a difference between the two conditions in the time window 350 – 500ms post word onset: familiar words were processed more negatively on left-frontal electrodes, indicating that the infants recognized the familiarized words. This negative effect of word familiarity appears to be quite stable for this age group. We see a similar negative effect of word familiarity in several 10-month-old word-segmentation studies in our lab (Junge, Hagoort & Cutler, 2010; Junge, Kooijman, Hagoort & Cutler, in prep.; Kooijman, Hagoort & Cutler, 2009), as well as in French 12-month-olds (Goyet & Nazzi, 2008).

Table 1. Example of an experimental block from Kooijman et al. (2005).

Familiarization: Ten repetitions of <u>hommel</u> (bumblebee) in isolation

Test:

De hommel vliegt van bloem tot bloem	The bumblebee flies from flower to flower
Het is een oude hommel met gele strepen	It is an old bumblebee with yellow stripes
Een viking reist naar verre landen	A Viking travels to places far away
Die kleine viking is niet sterk maar slim	That small Viking is not strong, but smart
Een kleine hommel zit op het gordijn	A small bumblebee is sitting on the curtain
Dat is de andere viking met veel vijanden	That is the other Viking with many enemies
Vaak kan een hommel erg hard zoemen	Often a bumblebee can buzz very loudly
Pieter zag die viking uit het Noorden	Pieter saw this Viking from the North

Kooijman and colleagues also used this design to look at Dutch 7-month-olds, an age group for which there is no behavioral evidence that they are able to segment words from speech (Kooijman, 2007; Kooijman, Johnson & Cutler, 2008). With ERPs, they found that 7-month-olds are able to recognize words in speech, although the group-averaged ERP for familiarity differed in polarity and distribution, compared to the first study. The majority of the 7-month-olds showed a positive effect of familiarity, most prominent on four right-frontal electrodes. Figure 1 illustrates the differences between the two age groups. The time window of the effect was slightly smaller, but again around 400 ms. This shows that 7-month-olds are able to recognize words from speech, although the underlying brain response differs from that of their older peers. There were some 7-month-olds, however, who showed a pattern similar to that of 10-month-olds.

Given that the ability to segment words from continuous speech is essential for language development, what does it mean that some 7-month-olds show this pattern, and others have a different pattern? Is this variability in ERP responses for word recognition related to later language development? In other words, is there a relationship between word segmentation ability and later language scores similar to that observed by Newman et al. (2006)? The measure of speech segmentation ability in the present study differs from that of Newman et al.'s (2006) study in several respects: our infants are as young as seven months, they have Dutch as their native language, and they were tested with ERPs rather than with behavioral methods. We obtained language quotients when these children were three years old to see if infants with a similar ERP pattern as their older peers differed in their later language profiles from the children who followed the overall 7-month-old pattern.

Several studies have investigated the relationship between language-related ERPs in infants and later language development (e.g. Friedrich & Friederici, 2006; Rivera-Gaxiola, Klarman, Garcia-Sierra, & Kuhl, 2005) or between infants with or without a familial risk of language impairments (e.g., Friedrich, Weber & Friederici, 2004; Torkildsen, Syversen, Gram Simonsen, Moen & Lindgren, 2007). Rivera-Gaxiola et al. (2005), for instance, used the mismatch negativity (MMN) paradigm to study native and non-native speech contrasts in typically developing 11-month-olds. For the non-native speech contrast, there was no overall group MMN effect. However, by looking at the individuals' ERP waves, there were two possible types that together were averaged out. Infants who showed a similar ERP for the non-native speech contrast as for the native contrast displayed smaller vocabularies at 18-30 months than infants who showed an ERP effect that differed in polarity for the non-native speech contrast. Together, these studies show that data from electrophysiological studies are suitable for measuring the relationship with later language development.

In the present study we explore the relationship between infants' ERPs for word segmentation at seven months and later language profiles at three years. We split the infants into two groups, depending on the average polarity on left-frontal electrodes in the 350 – 450 ms time window at seven months: Negative responders (whose individual ERP effect of familiarity resembled that of 10-month-olds) and Positive responders (whose individual effect resembled that of the overall 7-month-olds). The smaller plots in Figure 1 demonstrate this. We hypothesize that those infants with similar ERPs as the 10-month-olds will reveal higher language scores.

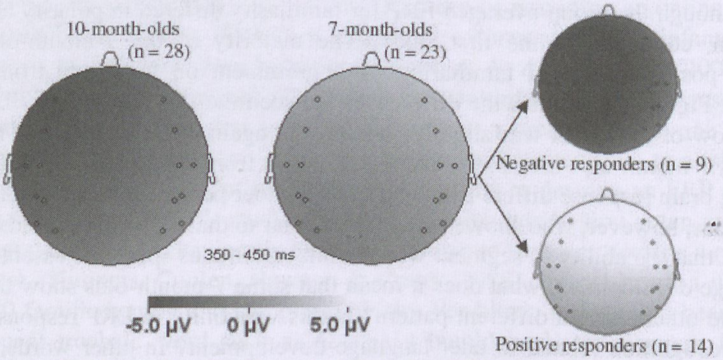

Figure 1: Mean distribution plots for the ERP effect of familiarity (familiar – unfamiliar words) in the 350–450 ms time window for 10- and 7-month-olds. The two smaller plots divide the 7-month-olds into the two subgroups.

2. Methods

2.1. Participants

Twenty-eight monolingual 7-month-old infants (14 girls), who were full-term (± 14 days from due date) from families with no history of language or neurological impairments, participated in the original ERP experiment on word segmentation. The majority of infants came from middle-class, college-educated parents. Twenty-three (11 girls) children returned for testing, a return rate of 82%. Two infants could no longer be reached and (parents of) three infants did not want to participate. The 23 children (all right-handed) were on average 36.3 months old (range 28.4 – 46.6 months). We subsequently divided the children into two groups, based on the polarity of the individual ERP effect of familiarity on left-frontal electrodes (where the effect for 10-month-olds was present): those who resembled the 10-month-olds ("Negative responders"), and those who did not ("Positive responders"). Figure 1 shows that of these 23 children, 9 children (3 girls) fell into the Negative responders group, and 14 children into the Positive responders group. They do not differ in number of trials per condition: Positive responders have on average 21 trials per condition per subject, and Negative responders 20 trials (t (21) = 0,551, p = .59; t (21) = 0, 099, p = .92 for familiar and unfamiliar words, respectively). They also did not differ in age during any of the tests (for the ERP experiment, Positive and Negative responders have a mean age of 217 and 218 days, (t (21) =-0,213, p = .83); for the follow-up study, 37.6 and 34.4 months, respectively (t (21) = 1,307, p = .21)). There were two Positive responders with a history of speech therapy.

2.2. Procedure and Materials

All children participated in two norm-referenced language tests, the "Reynell Test voor Taalbegrip" (van Eldik, Schlichting, Lutje Spelberg, van der Meulen & van der Meulen, 1995), measuring receptive language development, and the "Schlichting Test voor Taalproductie" (Schlichting, van Eldik, Lutje Spelberg, van der Meulen & van der Meulen, 1995), measuring productive language development. Together, the tests are a slightly modified translation of the Reynell Developmental Language Scales (Reynell, 1985) into Dutch. They are the established tests used in the Netherlands for measuring language development problems, and are norm-referenced over 1,000 normally developing children. The test results for each child are converted into language quotients (LQs), depending on the age of the child in months. These scores have a mean of 100 and a standard deviation of 15 points. A child is considered to have a risk of language impairment at an LQ below 85. Both tests distinguish between levels of difficulty, allowing older children to start at a more advanced level, and both are suitable for children between two and six years.

The children were individually tested by the first author, blinded to their earlier laboratory profiles. In the first session they participated in the Reynell Test voor Taalbegrip, measuring their LQs for comprehension. Here, they had to act out or point to requested objects. In the second session, which took place on average 8 days (range 1- 21 days) after the first session, they participated in two subtests of the "Schlichting test voor Taalproductie": the "Test voor Zinsontwikkeling", measuring LQs for sentence production, and the "Test voor Woordontwikkeling", measuring LQs for word production (i.e., expressive vocabulary development). In the first subtest, children are required to make sentences of a similar structure as the experimenter does on the basis of certain pictures or arrays of toys. In the second subtest children have to name things in pictures or finish the experimenter's sentences describing the pictures. In addition to both tests, parents were asked to complete a Dutch version of the "Speech and Language Assessment Scale" (Hadley & Rice, 1993), in which they had to rate their child's development on a variety of language skills compared to 'other children of the same age', starting from 1 ('very poor') to 7 ('very good').

3. Results

3.1. At seven months: Ability to segment words

To ensure that the subset of the 23 children who returned for follow-up testing was representative of the larger sample, we first repeated the analyses from Kooijman (2007). We performed repeated measures analyses of variance (ANOVAs) on the mean amplitudes in the selected time windows, with Familiarity (familiar vs., unfamiliar), Quadrants (4: left frontal, right frontal, left posterior, and right posterior), and Electrode (5; left frontal: F7, F3, FT7, FC3, C3; right frontal: F8, F4, FT8, FC3, C4; left posterior: LT, LTP, CP3, LP, P3; right posterior: RT, RTP, CP4, RP, P4) as variables. For all tests, we used the Huynh-Feldt epsilon correction, and report the original degrees of freedom and adjusted p-values. For the same time window (350 – 450 ms), we see again that although there was no main effect of Familiarity, the interaction between Familiarity and Quadrant was significant ($F(1, 22) = 0.86$, $p = .364$; $F(3,66) = 5.17$, $p = .005$, respectively). The distribution of the familiarity effect is similar to the original study, although it is now significant over the whole right-frontal quadrant ($F(1,22) = 4.355$, $p = .049$).

Having now established that the subset of children is representative of the full sample, we then tested whether, besides a difference in distribution and polarity, the Positive & Negative responders differed in the onset of the familiarity effect. Both groups have similar onset effects, with for Positive responders the effect starting at 100ms for right electrodes FT8 and RT, and for Negative responders starting at 110ms for left electrodes FT7 and LT. Both groups also do not differ in the familiarization period: a comparison of the ERPs for the first two versus the last two tokens of isolated words in the time window 200-500ms show again a main effect of Repetition ($F(1,21) = 5.132$, $p = 0.34$), but no interaction of Repetition x Group ($F(1,21) = .001$; $p = .973$), similar to that of the 10-month-olds.

3.2. Relation between ability to segment words at seven months and later language development at three years

Results for the follow-up standardized language tests show that all children achieved scores within or above the normal range. Overall, children have high LQs for comprehension ($m = 115.4$, $sd = 11.8$), for sentence production ($m = 113.9$, $sd = 14.7$), and for word production ($m = 118.9$, $sd = 11.2$). Their parents

Table 2. Correlation coefficients relating the language quotients and parental questionnaires at three years ($^{***}p < .001$ $^{**}p < .01$ $^{*}p < .05$).

	Sentence Production LQ	Word Production LQ	SLAS average
Comprehension LQ	.577**	.515*	.499*
Sentence production LQ		.411	.669***
Word production LQ	-	-	.326

rate their average language skills also as somewhat better than peers (m = 4.7, sd =0.9). These scores correlate highly with each other, as illustrated in Table 2.

Figure 2 shows that the children who already at seven months have similar ERPs as their older peers (Negative Responders) have significantly higher LQs for comprehension ($t(21) = -2.37$, $p = .027$) and for word production ($t(21) = -5.85$, $p < .001$), as well as almost significantly higher LQs for sentence production ($t(21) = -2.06$, $p = .052$), compared to children who at seven months follow the overall group pattern (Positive Responders). The Negative Responders perform on average at 1.5 standard deviations above the LQ mean.

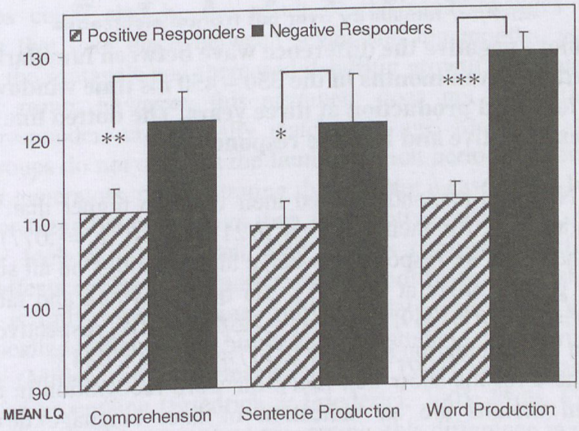

Figure 2. The three language quotients at three years split by group performances at seven months (*p <.001 **p <.05 *p <.10; error bars are one standard error from the mean).**

Further, across all 23 subjects, Figure 3 shows a significant correlation between the ERP effect and the LQ for word production: the more negative the difference wave between familiarized and unfamiliar words at seven months, the higher the LQ for word production at three years ($r_{bivariate} = -.45$, $p = .02$; with LQs for comprehension and sentence production partialled out, $r_{partial} = -.42$, $p = .06$). To assess the relative contribution of later language scores at three years and word segmentation at seven months, we used a discriminant function analysis with step-wise selection and a predictor inclusion criterion of $p = .05$, and the predictor variables of LQs for comprehension, sentence production, word production as well as the overall SLAS scores. Only the LQ for word production was significantly related to early segmentation ability, predicting correctly the segmentation ability for 21 of the 23 children.

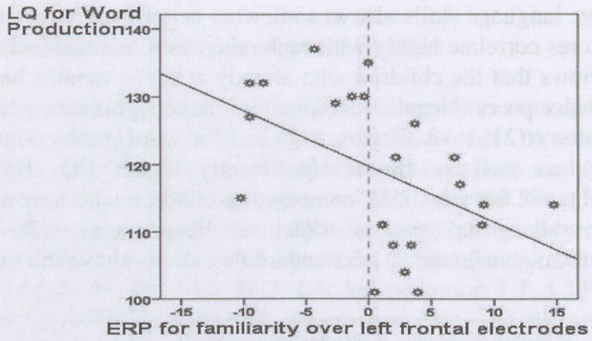

Figure 3: The more negative the difference wave between familiarized and unfamiliar words at seven months in the 350 – 450 ms time window, the higher the LQ for word production at three years. The dotted line indicates the split between Negative and Positive responders.

Parents of Negative responders rated their children higher than parents of Positive responders did for their children (t(21) = 1.86, p = .077). Figure 4 illustrates that the Negative responders receive higher ratings on all subscales of the SLAS. The groups differ at beyond p .05 on the syntax and talkativeness subscales (t(21) = 2.09, p = .049, and t(21) = 2.58, p = .018, respectively), and at beyond p .10 on the articulation subscale (t(21) = 1.82, p =.084).

Together, these results show that ERPs for word recognition in continuous speech at seven months are an indication of later language development. Negative responders have higher language scores than Positive responders. This is most prominent for expressive vocabulary scores at three years.

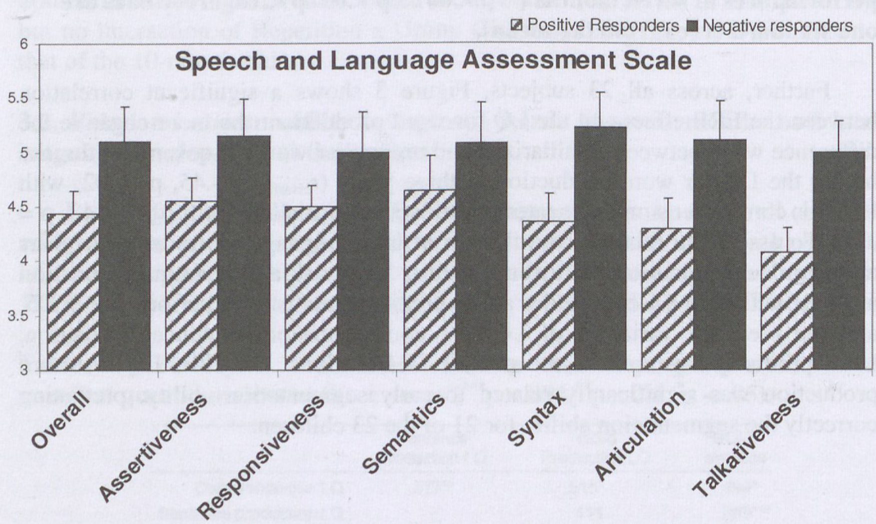

Figure 4: Group ratings on the SLAS: overall and per subscale.

4. Discussion

By comparing the individual ERP responses of 7-month-olds to the 10-month-old ERP data on word segmentation, we see that 7-month-old infants with an effect of familiarity similar in distribution and polarity as the 10-month-old overall group have higher later language scores than the remaining 7-month-olds. The differences of the ERP effect of familiarity between the Positive and Negative responders suggest that both groups use different underlying neural sources to achieve word recognition in continuous speech. Kooijman et al. (2008) point out that this difference in polarity and distribution between the two age groups could also be the result of the rapid changes of infant brain maturation that take place between seven and ten months, such as the slow closing of the fontanels and increased dendritic growth and pruning. Within the same age group, however, this argument does not hold: the Positive and Negative responders are virtually matched in age. Moreover, the finding that both subgroups do not differ in the familiarization period suggests that here they use similar generators, demonstrating that it is not a case of the brain being more matured for Negative responders than for Positive responders, or vice versa. If we further look at other infant ERP studies contrasting different ages, the observed effects appear to be quite stable over different ages, showing that with age there is only a trend going from a widely distributed effect towards a smaller, localized effect. This holds both for studies on known-unknown word processing (Mills, Coffey-Corina & Neville, 1997) as well as for studies on picture-word processing (Friedrich & Friederici, 2005; Mills, Conboy & Paton, 2005). For known-unknown word processing, this difference in distribution does not appear to stem from brain maturation, but from amount of language experience (Conboy & Mills, 2006; Mills, Plunkett, Prat & Schafer, 2005). Hence, it seems plausible that Positive and Negative responders use different neural generators to achieve the same result, which points to a difference in mechanisms used for recognizing words in running speech.

The question then turns to how one can explain this difference in use of mechanisms. Both prenatal (parental genetics, mother's general health and gestation period) and postnatal (family's socioeconomic status, parental education) factors have been identified among the influences that may alter the course of language development. Our subgroups do not differ, as far as we know, in these respects. One possible explanation, however, comes from Kuhl's "native language magnet theory-expanded" (NLM-e) model (Kuhl, Conboy, Coffey-Corina, Padden, Rivera-Gaxiola & Nelson, 2008). According to the NLM-e model, there is a critical period for infants, between six and twelve months, in which they develop neural networks specifically dedicated to native language processing, which in turn facilitates higher language learning. Infants who are more advanced in phonetic learning will also be more advanced in their next stage of language learning, that is, detection of word-like units. It is possible that the Positive responders are less advanced in their phonetic learning, thereby processing the continuous speech stream in a different manner than the

Negative responders do. When it comes to the easier task of recognizing words in isolation, however, Positive responders use the same mechanisms as Negative responders.

Our results cannot distinguish between speech segmentation skill as special or as bootstrapped from a more advanced mechanism of native speech processing. We have only records of later language profiles to demonstrate the importance of speech segmentation ability, no concurrent language scores at seven months. In fact, measuring language development at seven months is impossible, since the widely-used parental questionnaires are only standardized from eight months old (Fenson, Dale, Reznick, Bates, Hartung, Pethick & Reilly, 1993). In either case, it makes sense to assume that speech segmentation ability is an important precursor for later language development, because it is crucial for building a vocabulary. This study shows that a left-frontal negative amplitude for word familiarity as early as seven months is associated with later language profiles at three years. Other studies in our lab also link this negativity for word familiarity in continuous speech to future language development (Junge et al., 2010; Junge et al., in prep;).

Studies on isolated word processing, comparing familiar/known versus unfamiliar/unknown word processing, also report similar negative ERP effects, just as we have seen in our word segmentation studies (Thierry, Vihman, & Roberts, 2003; Mills et al., 1997). It is likely that for infants with a very limited vocabulary, the same mechanism is involved for word recognition in continuous speech as for known versus unknown word processing. Although Mills, Plunkett et al., (2005) showed that for 20-month-olds it is word meaning rather than word form familiarity that explains effects of familiarity, it is likely that the recognition mechanism has evolved from one that at a younger age is mainly sensitive to word form repetitions. It is also possible that the observed negativity does not index word repetition, but rather word learning. Research from adult studies on artificial language streams also shows a fronto-central negativity related to word repetition, which is explained as the on-line creation of a linguistic word-like representation (Cunillera, Toro, Sebastián-Gallés, & Rodríguez-Fornells, 2006). This contrasts, however, with the finding that word repetition in normal speech in adults is generally associated with a more positive amplitude, both for native and non-native speakers (e.g., Rugg, 1985; Snijders, Kooijman, Hagoort & Cutler, 2007). Even so, word form familiarity and online word learning are themselves likely to be related. What is clear is that a negative effect of word familiarity on left-frontal electrodes around 400 ms is related to later language development.

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