Title: More efficient learning at birth leads to better language skills at 2 years

Authors: Emma Suppanen¹, István Winkler², Teija Kujala¹, Sari Ylinen^{1,3}

Affiliations:

¹ Cognitive Brain Research Unit, Department of Psychology and Logopedics, Faculty of Medicine, University of Helsinki, Helsinki, Finland

² Institute of Cognitive Neuroscience and Psychology, Research Centre for Natural Sciences, Hungarian Academy of Sciences, Hungary

³ Cicero Learning, Faculty of Educational Sciences, University of Helsinki, Helsinki, Finland

Corresponding author: Emma Suppanen, Cognitive Brain Research Unit, Department of Psychology and Logopedics, Faculty of Medicine, Haartmaninkatu 3, FIN-00014 Helsinki, Finland; email: emma.suppanen@helsinki.fi

Running title: Newborns' learning links to language development

Acknowledgments:

The authors would like to thank all the families for participating, Tarja Ilkka, Anna-Riikka Smolander, Anastasia Gallen and Susanna Petäistö for their help with the EEG measurements, and Tommi Makkonen, Jaakko Kauramäki and Jaakko Sulkko for technical assistance. This project is conducted in co-operation with Hospital District of Helsinki and Uusimaa and supported by Research Funds of the University of Helsinki (project Predictive coding in Language Learning, awarded to SY), the Academy of Finland (project no 274058), the National Research Fund of Hungary (grant number K115385 to IW), and Eemil Aaltonen Foundation (awarded to ES).

Abstract

Infants are able to extract words from speech early in life. Here we show that the quality of word-form learning at birth predicts language development at the age of two years. Seventy-five neonates were familiarized with two spoken disyllabic pseudowords. We then tested whether the neonate brain predicts the second syllable from the first one by presenting a familiarized pseudoword frequently, and occasionally violating the learned syllable combination by different rare pseudowords. Distinct brain responses were elicited by predicted and unpredicted word endings, which suggests that the neonates had learned the familiarized pseudowords. The difference between responses to predicted and unpredicted pseudowords indexing quality of word-form learning significantly correlated with expressive vocabulary scores at 24 months in the same infant. These findings suggest that 1) neonates can memorize disyllabic words so that a learned first syllable generates predictions for the word ending, 2) early individual differences in the quality of word-form learning correlate with language outcome. This relationship helps early identification of infants at risk for language impairment.

Introduction

Learning to communicate by speech is a major developmental achievement for human infants. Although they appear to grasp speech quickly and spontaneously, it is one of the most complex tasks faced during infancy (e.g., Kuhl, 2004; Werker & Curtin, 2005). However, there is considerable variation in children's language development (Fenson et al., 1994). For example, Fenson and colleagues (1994) found that the number of words produced at 2 years ranged from 7 to 668. Learning effects tend to accumulate, and it is therefore crucial to support those with poorer language skills or delayed language development as early as possible. Since early diagnostics is an essential part of remediation (Sigman et al., 2014), we need to develop tools for detecting infants at risk for poor language skills or language impairments before we can measure the actual language outcomes from behavior. The present study aimed to find a neural index of later language development, which can be safely measured from the brain activity of newborn infants with electroencephalography (EEG).

To this end, we measured neural responses reflecting word-form learning in newborns in a stimulus paradigm utilizing predictive processing, because predictive processes have been shown to play an important role in language functions (Pickering & Garrod, 2013; Kuperberg & Jaeger, 2016). These processes are used to recognize words (Gagnepain, 2012) and predict upcoming speech sounds based on the rules of the native language (DeLong et al., 2005; Ylinen et al., 2016). Further, predictive information has been found to increase the perceived clarity of speech when acoustic clarity is degraded (Wild et al., 2012) and to decrease reaction times to words (for a review, see Kuperberg & Jaeger, 2016). In addition, infants appear to utilize predictive inference from birth (Ruusuvirta et al., 2009; Näätänen et al., 2010; Trainor, 2012; Háden et al., 2015), and they extract regularities from speech-like sequences (Teinonen et al., 2009; François et al., 2017; Suppanen et

al., 2019). Linking infant predictive processing with language development, Ylinen and colleagues (2017) have demonstrated that predictability facilitates word recognition and learning in 12-month-old infants.

One consequence of learning is that one can infer to the whole from detecting a part, as it generally occurs in everyday perception (Gregory, 1980). Because predictive processing is functional at birth and the infant brain arguably uses it in speech processing, we hypothesized that the precision of neonates' predictive processing for familiarized pseudowords varies as a function of their learning ability. We extracted a measure of predictive precision from electric neonatal brain responses utilizing the infant equivalent of auditory mismatch negativity (MMN, Näätänen et al., 1978; for a recent review, see Fitzgerald & Todd, 2020), the mismatch response (MMR¹). MMN/MMR is a prediction error signal (Winkler et al., 1996; for reviews see Garrido et al., 2009; Bendixen et al., 2012) elicited by infrequent "deviant" sounds violating some regularity of the preceding stimulus sequence, such as a repeating "standard" sound. In addition to MMR to acoustic deviations, an unexpected word ending elicits a word-level prediction error MMR, because hearing the beginning of a familiar word generates a prediction for its ending (Ylinen et al., 2017). We employed this effect for exploring word-form learning in sleeping infants and tested whether a neural measure of the quality of word-form learning could predict later language outcomes. We hypothesized that its variation across neonates will positively correlate with measures of the infants' subsequent language development. Language outcome was assessed as the quality of speech production at 24 months of age.

Methods

¹ Note that in infants, the ERP modulation elicited by deviants can appear with either polarity (for a review, see Kushnerenko et al., 2013); therefore, the infant equivalent of MMN is termed the mismatch response (MMR). MMR is useful measure for studying neonates because it can be recorded from sleeping infants (e.g., Alho et al., 1990).

Participants

75 healthy, full-term newborn infants (see Table 1) born into Finnish-speaking families participated in the study. The study protocol was approved by the Ethics Committee for Gynecology and Obstetrics, Pediatrics and Psychiatry of the Hospital District of Helsinki and Uusimaa, and EEG measurements were conducted in Jorvi hospital in Espoo, Finland in compliance with the Declaration of Helsinki. Written informed consent was obtained from at least one of the parents of each participant prior to the experiment. Data of 11 infants were excluded due to technical problems, or not reaching the criterion of 50 accepted epochs per stimulus type, resulting in the inclusion of 64 infants in the study.

Table 1 Description of the participants (mean, and standard deviation [SD]).

		All participants		Included participants		Participants included in correlation analysis	
Variable		Mean	SD	Mean	SD	Mean	SD
N (male/female)		75 (41/34)	N/A	64 (31/33)		45 (22/23)	N/A
Gestational age		40.1	0.9	40.1	0.9	40.2	1.0
(weeks)							
Age at measurement		9.3	4.4	9.0	4.4	9.0	4.6
(days)							
Birth weight (g)		3530	423	3532	428	3555	404
5-min Apgar score		7-10		7-10		7-10	
(range)							

Stimuli

Stimuli were recorded in a sound-isolated studio (microphone: Rode NT2-A, Rode Microphones, Sydney, Australia; audio interface: Digidesign Digi 002, software: Pro Tools 12, both: Avid Audio, Berkeley, CA, USA) where a female and a male native Finnish speaker repeated (pseudo)words several times. The stimulus material included pseudowords /'kut:o/, /'tek:a/, /'tet:o/, /'kup:e/ and a word /'kuk:a/. All of these are legal with respect to the Finnish phonology. Syllables were isolated from their context and assessed by two native Finnish speakers. From both the male and the female speaker, for each syllable, the two most prototypical exemplars without clear co-articulatory cues revealing the original context were chosen for the experiment. The syllables were then processed with Praat (Boersma & Weenik, 2010): durations and intensities were equalized as closely as possible, separately for the stressed and unstressed positions. The main parameters of the syllables are shown in Table 3. The (pseudo)words presented in the study were constructed by pairing the exemplars of the first-position (stressed) syllables with the exemplars of the second-position (unstressed) syllables in all possible combinations, separately for the male and female speaker (4 combinations/(pseudo)word/speaker).

The total duration of the (pseudo)words was 426 ms: the first syllable was ≈ 90 ms, a silent pause mimicking the occlusion phase of a stop consonant was ≈ 210 ms, and the second syllable was ≈ 126 ms. Thus, the second syllable onset was at ≈ 300 ms from the onset of the (pseudo)word. The interstimulus interval (offset to onset) was ≈ 510 ms. The stimuli were presented with Presentation 17.2. Software (Neurobehavioral Systems Ltd., Berkeley, CA; USA) via a Genelec speaker placed approximately 40 cm from the infant's head directly in front of the infant. The approximate sound level was 65 dB sound pressure level (SPL).

Study design

The experiment consisted of two phases, the familiarization phase and the test phase. In the familiarization phase pseudowords /'kut:o/ and /'tek:a/ (referred as *AB* and *CD*, respectively, where *A*, *B*, *C*, and *D* represent different syllables) were presented ($p = 0.5$) in three stimulus blocks, each containing 250 stimuli and lasting for 11.7 minutes, altogether. We expected the infants to form an internal model of the pseudowords presented in the familiarization phase so that familiar initial syllables would evoke predictions for the syllable to follow them (i.e. *A* evokes the prediction of *B*, whereas *C* evokes the prediction of *D*). 80% of the stimuli were spoken by one speaker, and the remaining by the other speaker. Infants either heard only predominantly male-speaker or only predominantly female-speaker blocks. The test phase was presented in four oddball blocks, each containing 750 stimuli, 46.8 minutes overall. The order of the stimuli was pseudo-randomized so that a deviant was followed by at least two standards and each block started always with at least eight standards. The blocks were homogenous with respect to the gender of the speaker and each infant heard either male-only or female-only blocks. The speaker gender variables were fully crossed both in the familiarization and the test phase in order to balance the possible effects of the speaker's gender, resulting in four groups of participants (average 19 participants in each). The four groups were collapsed in the current data analysis (the effects of speaker gender will be assessed in a separate study).

In the test phase, an oddball paradigm with repetitive standard and occasional deviants was used to probe prediction and learning effects (see Figure 1). The familiar pseudoword *AB* (/ 'kut:o/; $p = 0.8$) served as the frequent standard stimulus in an oddball sequence with four kinds of rare deviants: *AD*, *AX* (*X* denoting a novel syllable), *CD*, and *CB* ($p = 0.05$ for each). 1) the other familiarized pseudoword *CD* (/ 'tek:a/; familiar pseudoword deviant), 2) a combination of two

familiar syllables, forming a non-familiarized pseudoword *CB* (/ˈtɛt:o/), 3) the other combination of familiar syllables forming a non-familiarized word *AD* (/kuk:a/; a flower), and 4) a pseudoword starting out as the standard but ending with a novel (not familiarized) second syllable *AX* (/kup:e/).

Figure 1. An example of stimulus sequences. *AB* and *CD* were introduced in the familiarization phase, and familiar word beginnings were expected to generate predictions of the endings. Note that a deviant was followed by at least two (in most cases more) standards.

For *AD* and *AX*, syllables *D* and *X* were hypothesized to elicit two overlapping MMRs because 1) they violated the sequence-level regularity (by appearing infrequently within the sequence) and 2) the learned word-level prediction (Ylinen et al., 2017) induced by the first syllable (*A* → *B*). The response to the novel (not familiarized) syllable *X* was also expected to evoke a novelty response (Kushnerenko et al., 2013). For *CD* and *CB*, the initial syllable *C* was expected to elicit the sequence-level MMR since it breaks the repetition of *AB*. The final syllables, in turn, were hypothesized to evoke different responses for the familiarized pseudoword *CD* and the unfamiliar pseudoword *CB*, because *B* violated the learned *C* → *D* prediction, while *D* did not (Ylinen et al., 2017).

The difference between the responses to the second syllables of *CD* and *CB*, which measured how well neonates had learned to expect *D* after hearing *C*, provided an index for the quality (precision) of word-form learning, which had taken place during the familiarization phase. Note that both *B* and *D* appeared as the second syllable of a familiarized pseudoword with *B* matching the second syllable of the standard (*AB*) stimulus of the oddball sequence. Therefore, difference between the responses to these syllables cannot be due to “syllable learning” (or even syllable-position learning), nor can it be explained by *B* eliciting some deviation-related response with respect to the frequent standard stimulus (*AB*).

Data collection

Infants were sleeping on their back in a crib while EEG was recorded with 500 Hz sampling rate, from DC to 100 Hz with 18 active electrodes (headcap: ActiCap; amplifier: BrainProducts QuickAmp 10.08.14; software BrainVision Recorder 1.20.0801; all: Brain Products GmbH, Gilching, Germany) placed according to the international 10/20 system at Fp1/2, F7/8, F3/4, Fz, C3/4, Cz, P7/8, P3/4, Pz, Oz) and over the mastoids (LM and RM). The data were referenced to the average of all electrodes during the recording.

When the infants reached the age of 24 months, their parents filled out the Finnish version (Lyytinen, 1999) of the MacArthur-Bates communicative development inventory (CDI; Fenson et al., 1994). 56 of the 75 families (75%) provided this information.

Data analysis

We only report here the data collected in the test phase. EEG signals were pre-processed with BESA Research 6.0 (Besa GmbH, Gräfelting, Germany) and MATLAB Release 2018b (The MathWorks, Inc., Natick, Massachusetts, USA), using EEGLab 2019.0 (Delorme and Makeig, 2004) and in-house Matlab scripts (CBRUPlugin2.1b, Tommi Makkonen, Cognitive Brain Research Unit, University of Helsinki). First, the signals were bandpass-filtered offline (high-pass 0.5 Hz, low-pass 30 Hz, slope 24 dB/octave) and segmented into -100 to 800 ms epochs with respect to word onset, separately for each stimulus and participant. The responses to the two standard stimuli immediately following a deviant and epochs with their amplitude exceeding $\pm 80 \mu\text{V}$ were excluded from the analysis. After artefact rejection, the average number of remaining responses to the standards was 992 (SD = 126), while that to the deviants was 128 (SD = 17), separately for each deviant. The signals were then re-referenced to the average of the two mastoid electrodes.

Epochs were averaged separately for each stimulus type. The baseline was corrected by the average voltage within time-windows immediately preceding the divergence point of the deviants. The deviants *AD* and *AX* diverged from the standard at 300 ms. They were baseline-corrected by the average voltage in the 300 ms interval before the second syllable onset to compensate for the response to the first syllable. The deviants *CD* and *CB* started with a different initial syllable than the standard. They were baseline-corrected by the 100 ms pre-stimulus interval. The averaged response to the standard stimulus (baseline-corrected the same way as the corresponding deviant) was subtracted from those to the deviants in order to quantify the deviance-related responses. Two time-windows (time window 1: 200 – 300 ms, and time window 2: 550 – 650 ms) were selected for statistical analysis based on previous literature (especially 18) and considering the onset of the second syllable. Time window 1 was only employed for deviants *CD* and *CB*, because *AD* and *AX* are identical to the standard in this period, which is fully covered by the baseline for these two deviants.

Statistical analysis was carried out with SPSS 25 (IBM, Armonk, New York, US). Normality of the data distributions was tested using the Shapiro-Wilk test (W). To test whether the deviance related responses were statistically significant ($\alpha = .05$), the mean voltages, measured for the average of the three central and three frontal electrode locations (six electrode locations, altogether) from the selected time windows, were submitted to one sample Student's *t*-tests (i.e., comparing them to zero). Effect sizes are reported as Cohen's *d*. Repeated measures ANOVAs (2 x 2 x 3 levels) were conducted on the difference amplitudes separately for each time window and first syllable (i.e. time window 1 testing was only done for deviants starting with the *C* syllable, while time window 2 testing was done both for deviants starting with *A* and *C*, but separately, because the baselines differ between them). The ANOVA factors were *Deviant* (*CD* vs. *CB* or *AD* vs. *AX*), *Frontality* (F vs. C line) and *Laterality* (left vs. middle vs. right [electrodes F/C 3, z, and 4]). We will only report the effects involving the *Deviant* factor in Results, as only those are related to our hypotheses; the full set of results are shown in Tables 2-1, 2-2, 2-3. When sphericity could not be assumed, Greenhouse-Geisser correction was applied where applicable and the ϵ correction factor is reported. Significant ($\alpha = .05$) effects were followed up by Bonferroni-corrected pairwise comparisons. Cohen's *d* values were calculated for each pairwise comparison.

Given that the amplitude of the prediction error response is assumed to reflect the specificity of the violated prediction (Friston, 2005; Winkler, 2007), the difference between the electrical brain response amplitudes elicited by predicted and unpredicted word endings was used for testing the association between learning effects at birth and later language development (Ylinen et al., 2017). The mean fronto-central amplitude for *CB* (the average of six locations along the F and C lines) was subtracted from that for *CD* in time window 2. (Note that the direction of this subtraction is arbitrary as there is no external reference for the difference between two responses.) This variable was then rank correlated with the mean length of utterance at 24 months (taken from the CDI), which is a

standard index of general language development (Rice et al., 2006; Kunnari et al., 2012; Jalilevand & Ebrahimipour, 2014). 45 infants, who had all required measures, could be included in this analysis.

Results

All deviant stimuli elicited a response significantly differing from the response to the standard (see Figures 2 and 3 as well as Figure 2-1; Table 2 for the amplitudes and *t*-test results) suggesting that the infants' brain could distinguish the rare stimuli from the frequent one.

Repeated measures ANOVAs [*Deviant* (*CD* vs. *CB* and, separately, *AD* vs. *AX*) $\times$ *Frontality* (Frontal vs Central) $\times$ *Laterality* (left vs. middle vs. right)] for the amplitude measures from time window 1 (200 – 300 ms) did not yield any significant effect involving the *Deviant* factor. However, in time window 2 (550 – 650 ms), for *CD* and *CB* there was a significant main effect of *Deviant* [$F(1, 63) = 14.5$, $p = .001$, $\eta^2 = 0.19$], with the response to *CB* being significantly more negative than that to *CD* [$p = .001$, $d = 0.48$]. For *AD* and *AX*, there was also a significant main effect of *Deviant* [$F(1,63) = 5.98$, $p = .017$, $\eta^2 = 0.09$] and a significant *Deviant* $\times$ *Frontality* $\times$ *Laterality* interaction [$F(2, 126) = 4.86$, $p = .021$, $\epsilon = 0.659$, $\eta^2 = 0.07$]. According to Bonferroni-corrected pairwise comparisons, the deviant *AX* elicited a significantly more positive response than *AD* ($p = .017$, $d = 0.31$), at the Fz [$p = .038$, $d = 0.27$], F4 [$p = .002$, $d = 0.41$], C3 [$p = .018$, $d = 0.21$] and C4 [$p = .033$, $d = 0.27$]. For the full ANOVA results, see Tables 2-1, 2-2, and 2-3.

Table 2. Group-averaged ($N = 64$) deviant-minus-standard difference amplitudes in the two time windows (time window 1 only for the *CD* and *CB* deviants, because *AD* and *AX* do not yet deviate from *AB* at this latency) together with the results of the one-sample *t*-tests, separately for each deviant. Mean amplitudes (in bold) and standard deviations (in parentheses) are given– for the

average of the six selected frontal and central channels. One-sample t-statistics (t, df – degrees of freedom, in parentheses, p – significance level, Cohen’s d – effect size) are also shown.

Difference response	CD /tek:a/	CB /tet:o/	AD /kuk:a/	AX /kup:e/
Time window 1	2.00 (1.4)	1.98 (1.8)		
(200 – 300 ms)	$t(63) = 11.19$, $p = .001$, $d = 1.4$	$t(63) = 8.86$, $p = .001$, $d = 1.11$		
Time window 2	.51 (1.4)	-.38 (1.4)	.66 (1.4)	1.37 (1.7)
(550 – 650 ms)	$t(63) = 2.97$, $p = .004$, $d = 0.37$	$t(63) = -2.16$, $p = .034$, $d = -0.27$	$t(63) = 3.81$, $p = .001$, $d = 0.47$	$t(63) = 6.61$, $p = .001$, $d = 0.83$

Correlation analysis showed that the learning effect operationalized by the amplitude difference of word-level prediction error in time window 2 (*CB-minus-CD*; average of the six frontal and central electrodes) significantly rank correlated with the mean length of utterance measured at 24 months of age ($\rho = 0.33$, $p = .025$, $n = 45$). The trend line for the significant correlation is shown in Figure 4.

Figure 2. Group-averaged ($N = 64$) frontal (electrode Fz) deviant-minus-standard difference responses. (a) The deviants CD (/tek:ɑ/, the familiarized pseudoword) and CB (/tet:o/, an unfamiliar pseudoword consisting of the combination of the two familiar syllables). (b) The deviants AD (/kuk:ɑ/, an unfamiliar word consisting of the combination of two familiar syllables) and AX (/kup:e/, a novel pseudoword starting out as the standard, but ending with a syllable that was not familiarized). The time windows (200 – 300 ms and 550 – 650 ms) used for measuring the deviant-related responses are marked with light gray vertical rectangles, and the baselines used for baseline correction with pink horizontal rectangles. The y-axis is at 0 ms (onset of the first syllable) and the onset of the second syllable is marked by a black arrow. The significant (see Table 2) deviant responses showed that the newborns were able to differentiate each of the four different deviants from the standard. The difference between the responses to CB and CD in the second time window served as the measure of the quality of word-form learning.

Figure 3 The scalp distributions for the group-averaged ($N = 64$) neural activity (mean neural response amplitudes) in Time window 1 corresponding to the first syllable (CD and CB, only) and in Time window 2 corresponding to the second syllable. These distributions are consistent with those previously observed for the MMR, indicating summed activity from the auditory brain areas (for review see Kushnerenko et al., 2013).

Figure 4. Regression (N=45, see Methods) between the neonatal word-learning effect reflected by the fronto-central CD-minus-CB brain response amplitude difference and the mean length of utterance (MLU) at 24 months. The positive correlation means that larger word-learning effect at birth is associated with a higher expressive vocabulary at 24 months.

Discussion

The current study investigated whether word-form learning from speech exposure at birth predicts later language development. Word-form learning was assessed by measuring ERP responses to pseudo(words) starting with a syllable identical to a previously familiarized pseudoword but ending with a different syllable. If learned, the first syllable of the familiarized pseudowords was expected to induce predictions for their endings. Violating these predictions should elicit a word-level prediction error response in the brain (Ylinen et al., 2017). The amplitude of the prediction error response is assumed to reflect the specificity of the violated prediction (Friston, 2005; Winkler 2007). Therefore, the difference between the brain's response to predicted and unpredicted

endings can be used to assess the quality of the word-form learning. We found that this measure significantly correlated with the mean length of utterance (MLU) assessed through the CDI at 24 months, which is a proxy of general language development (Rice et al., 2006; Kunnari et al., 2012; Jalilevand & Ebrahimipour, 2014).

As expected, all four rare deviants elicited significant MMRs, suggesting that the infants discriminated them from the standard and detected that they violated the regularity of the oddball test sequence (i.e., the repetition of the standard). The deviance-related responses observed in time window 1 (200 – 300 ms) reflect the “classical” sequence-related MMR to the acoustic deviance of the first syllable (CD and CB vs. AB) (e.g. Háden, et al., 2016). The pattern of results obtained for time window 2 (550 – 650 ms) stem from three sources. 1) Violating the sequential regularity (AD and AX) could have evoked the “classical” sequential MMR by their second syllables being acoustically different from the second syllable of the repeating standard. Their responses in time window 2 show the same (positive) polarity as the response to the acoustic sequence-related deviance observed for CB and CD in time window 1 (see Figure 1). 2) AX elicited a more positive response than AD, likely due to the novelty response (Kushnerenko et al., 2013), as X was the only syllable in the test sequence to which infants were not previously familiarized. This interpretation is also supported by the significant scalp distribution difference between the AD and AX responses. 3) Violating word-level prediction by the second syllable (AD, AX, and CB) probably elicited a prediction error response (Gagnepain, 2012; Ylinen et al., 2017). Within the current stimulus paradigm, this can only be proven for CB, the response to which differed significantly from that to the standard AB despite both of them ending with the same second syllable. The difference between CB and AB shows up as a negative displacement, which suggests that word-level prediction violations elicit a negative-polarity response (see Figure 2). Note that, unlike for AD and AX, word-level prediction

error for CB can only be based on word-form learning during familiarization, because CB and CD appeared with the same (low) probability within the test sequence.

Based on the assumption that the precision of the violated prediction modulates the resulting prediction error (Friston, 2005; Winkler, 2007), for the current word-level predictions (Ylinen et al., 2017), the strength of the difference between the CB and CD responses in time window 2 can be assumed to reflect word-form learning. The across-infants variation in the size of this difference should then index the quality of word-form learning in infants. These assumptions allowed us to test whether word-learning skills at birth are linked with later language development. Our word-level prediction-error based measure of word-form learning in neonates significantly correlated with the mean length of utterance (MLU) at 24 months. Thus, the current data demonstrate that the quality of word-form learning at birth is an important determinant of later language development. Based on these findings, we argue that brain responses for word-level predictions can be used as a neonatal index of subsequent language development. This has important implications for very early detection and remediation of infants with risk for language impairment. To determine the role of our learning index as potential indicator of language impairments, further research should target infants with familial risk for various language impairments.

Our results on newborns are in line with those of Ylinen and colleagues (2017) who looked at correlation between prediction error responses and language skills cross-sectionally at 12 months and found a strong correlation between prediction error and receptive vocabulary. The current results support these earlier findings by demonstrating similar effects in a larger number of participants. Importantly, our results add a critical longitudinal aspect to the findings of Ylinen and colleagues (2017). Since we studied newborn infants, our findings also corroborate recent

suggestions that predictive inference facilitates even the earliest learning of word forms (Ylinen et al., 2017; Havron et al., 2019).

In conclusion, we found that word-form learning at birth predicts language skills at 24 months. We showed that newborn infants can learn word-like items from a short exposure and use this knowledge to generate predictions of following syllable succession. These results further suggest that predictive processing is innate, and it likely facilitates even the earliest recognition and learning of word-forms. Revealing the role of predictive processing in early language development may have important implications for detecting and supporting infants at risk for language impairment.

References

- Alho, K., Sainio, K., Sajaniemi, N., Reinikainen, K., Naatanen, R., & Näätänen, R. (1990). Event-related brain potential of human newborns to pitch change of an acoustic stimulus. *Electroencephalogr Clin Neurophysiol* 77:151–5.
- Bendixen, A., SanMiguel, I., & Schröger, E. (2012). Early electrophysiological indicators for predictive processing in audition: a review. *International Journal of Psychophysiology*, 83:120-131.
- Boersma, P. & Weenink, D. (2010). Praat: doing phonetics by computer. Version 6.0.12 [software]. Downloaded March 7. Available from: <http://www.praat.org/>
- DeLong, K. A., Urbach, T. P., & Kutas, M. (2005). Probabilistic word pre-activation during language comprehension inferred from electrical brain activity. *Nature neuroscience*, 8:1117.
- Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of neuroscience methods*, 134:9-21.
- Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D. J., Pethick, S. J., Tomasello, M., Mervis, C. B. & Stiles, J. (1994). Variability in early communicative development. *Monographs of the society for research in child development*, i-185.

- Fitzgerald, K., & Todd, J. (2020). Making sense of Mismatch Negativity. *Frontiers in Psychiatry*, 11:468. doi: 10.3389/fpsyt.2020.00468
- François, C., Teixidó, M., Takerkart, S., Agut, T., Bosch, L., & Rodriguez-Fornells, A. (2017). Enhanced Neonatal Brain Responses To Sung Streams Predict Vocabulary Outcomes By Age 18 Months. *Scientific reports*, 7:12451.
- Friston, K. (2005). A theory of cortical responses. *Philosophical transactions of the Royal Society B: Biological sciences*, 360:815-836.
- Friston, K., Kilner, J., & Harrison, L. (2006). A free energy principle for the brain. *Journal of Physiology-Paris*, 100:70-87.
- Gagnepain, P. H. (2012). Temporal predictive codes for spoken words in auditory cortex. *Current Biology*, 22:615-621.
- Garrido, M. I., Kilner, J. M., Stephan, K. E., & Friston, K. J. (2009). The mismatch negativity: a review of underlying mechanisms. *Clinical Neurophysiology*, 120:453-463.
- Gregory, R. L. (1980). Perceptions as hypotheses. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 290:181-197.
- Háden, G. P., Németh, R., Török, M., & Winkler, I. (2015). Predictive processing of pitch trends in newborn infants. *Brain research*, 1626:14-20.
- Háden, G. P., Németh, R., Török, M., & Winkler, I. (2016). Mismatch response (MMR) in neonates: Beyond refractoriness. *Biological psychology*, 117:26-31.
- Havron, N., de Carvalho, A., Fiévet, A. C., & Christophe, A. (2019). Three-to four-year-old children rapidly adapt their predictions and use them to learn novel word meanings. *Child development*, 90:82-90.
- Jalilevand, N., & Ebrahimipour, M. (2014). Three measures often used in language samples analysis. *Journal of Child Language Acquisition and Development*, 2:1-12.
- Kuhl, P. K. (2004). Early language acquisition: cracking the speech code. *Nature reviews neuroscience*, 5:831-843.
- Kunnari, S., Yliherva, A., Paavola, L., & Peltoniemi, O. M. (2012). Expressive language skills in Finnish two-year-old extremely-and very-low-birth-weight preterm children. *Folia Phoniatrica et Logopaedica*, 64:5-11.

- Kuperberg, G. R., & Jaeger, T. F. (2016). What do we mean by prediction in language comprehension?. *Language, cognition and neuroscience*, 31:32-59.
- Kushnerenko, E. V., Van den Bergh, B. R., & Winkler, I. (2013). Separating acoustic deviance from novelty during the first year of life: a review of event-related potential evidence. *Frontiers in psychology*, 4:595.
- Lyytinen, P. (1999). Communicative and language development inventory. Finnish version. Jyväskylä: Niilo Mäki Institute.
- Näätänen, R., Gaillard, A.W.K., & Mäntysalo, S. (1978). Early selective attention effect on evoked potential reinterpreted. *Acta Psychologica*, 42:313-329.
- Näätänen, R., Astikainen, P., Ruusuvirta, T., & Huotilainen, M. (2010). Automatic auditory intelligence: An expression of the sensory–cognitive core of cognitive processes. *Brain research reviews*, 64:123-136.
- Pickering, M. J., & Garrod, S. (2013). An integrated theory of language production and comprehension. *Behavioral and Brain Sciences*, 36:329-347.
- Rice, M. L., Redmond, S. M., & Hoffman, L. (2006). Mean length of utterance in children with specific language impairment and in younger control children shows concurrent validity and stable and parallel growth trajectories. *Journal of Speech, Language, and Hearing Research*, 49:793-808
- Ruusuvirta, T., Huotilainen, M., Fellman, V., & Näätänen, R. (2009). Numerical discrimination in newborn infants as revealed by event-related potentials to tone sequences. *European Journal of Neuroscience*, 30:1620-1624.
- Sigman, M., Peña, M., Goldin, A. P., & Ribeiro, S. (2014). Neuroscience and education: prime time to build the bridge. *Nature neuroscience*, 17:497-502.
- Suppanen, E., Huotilainen, M., & Ylinen, S. (2019). Rhythmic structure facilitates learning from auditory input in newborn infants. *Infant Behavior and Development*, 57:101346.
- Teinonen, T., Fellman, V., Näätänen, R., Alku, P., & Huotilainen, M. (2009). Statistical language learning in neonates revealed by event-related brain potentials. *BMC Neurosci.*, 10:21.
- Trainor, L. J. (2012). Predictive information processing is a fundamental learning mechanism present in early development: evidence from infants. *Int. J. Psychophysiol.* 83:256-258.

- Werker, J. F., & Curtin, S. (2005). PRIMIR: A developmental framework of infant speech processing. *Language learning and development*, 1:197-234.
- Wild, C. J., Davis, M. H., & Johnsrude, I. S. (2012). Human auditory cortex is sensitive to the perceived clarity of speech. *Neuroimage*, 60:1490-1502.
- Winkler, I., Karmos, G., & Näätänen, R. (1996). Adaptive modeling of the unattended acoustic environment reflected in the mismatch negativity event-related potential. *Brain research*, 742:239-252.
- Winkler, I. (2007). Interpreting the mismatch negativity. *Journal of Psychophysiology*, 21:147-163.
- Winkler, I., & Czigler, I. (2012). Evidence from auditory and visual event-related potential (ERP) studies of deviance detection (MMN and vMMN) linking predictive coding theories and perceptual object representations. *International Journal of Psychophysiology*, 83:132-143.
- Winkler, I., & Schröger, E. (2015). Auditory perceptual objects as generative models: Setting the stage for communication by sound. *Brain and Language*, 148:1-22.
- Ylinen, S., Huuskonen, M., Mikkola, K., Saure, E., Sinkkonen, T., & Paavilainen, P. (2016). Predictive coding of phonological rules in auditory cortex: A mismatch negativity study. *Brain and language*, 162:72-80.
- Ylinen, S., Bosseler, A., Junttila, K., & Huotilainen, M. (2017). Predictive coding accelerates word recognition and learning in the early stages of language development. *Developmental science*, 20:1-13.